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Revision 0

Digital Full-Scope Mockup of a Conventional Nuclear Power Plant Control Room, Phase 1: Installation of a Utility Simulator at the Idaho National Laboratory

Ronald L. Boring, Vivek Agarwal,
Jeffrey C. Joe, and Julius J. Persensky

June 2012

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EXECUTIVE SUMMARY

Nuclear power accounts for 20-25% of current base load electricity generation in the United States (U.S.), and does so in a manner that is cost competitive with other base load energy sources, such as coal, and without the release of carbon into the atmosphere. Low carbon replacement technologies that are an effective provider of base load electricity at a national scale and cost competitive have yet to materialize. Without suitable replacements for nuclear power, its generating capability in the U.S. must be maintained. This means it is imperative to ensure the continued safe and efficient operation of the current fleet of nuclear power reactors.

The Light Water Reactor Sustainability (LWRS) Program is a research, development, and deployment program sponsored by the United States Department of Energy (DOE). The program is operated in close collaboration with industry research and development (R&D) programs to provide the technical foundations for licensing and managing the long-term, safe, and economical operation of nuclear power plants (NPPs) that are currently in operation. In short, the LWRS program focuses on research that contributes to the national policy objectives of energy security and economic sustainability.

One of five principal R&D pathways addressing the Strategic Program Goals of the LWRS Program is Advanced Instrumentation, Control, and Information Systems Technologies. The strategic objective of this pathway is to establish a technical basis for new advanced instrumentation and control (I&C) technologies needed to achieve safety and reliability of operating nuclear assets. This objective is being achieved by carrying out an R&D program that is developing scientific knowledge as a necessary first step in implementing new technologies in nuclear energy systems.

The LWRS Program is working closely with nuclear utilities to develop I&C technologies and solutions to help ensure the safe life extension of current reactors. One of the main areas of focus is control room modernization. Existing control rooms are almost entirely analog, hardwired, and manually operated control systems. Since analog technologies are no longer readily available, digital control systems are the required replacement systems for modernization. While utilities have modernized many parts of their control rooms, operating constraints and technical challenges have limited large scale, high-risk/high-reward modernization activities.

The LWRS Program, and this LWRS R&D demonstration project in particular, are designed to mitigate the risk that industry faces from large scale control room modernization. The Idaho National Laboratory (INL) is developing the state-of-the-art Human System Simulation Laboratory (HSSL). At the heart of the HSSL is a reconfigurable control room simulator that can be used to develop and test the implementation of newer, digital control room systems. The HSSL will provide industry and researchers a naturalistic test environment of control room crew activities, and make it possible to test and refine advanced I&C concepts and novel human-system interface (HSI) elements prior to their implementation in NPP control rooms. By using the HSSL as a test environment, industry can take advantage of the enhanced capabilities of digital systems beyond plant control and protection functions, including better support for automating work processes, improved error detection and correction capabilities, and greater situation awareness through advanced visualization technologies. The end objective for the industry is to lower operational costs while at the same time improving plant performance, safety, and reliability.

This report describes the main Fiscal Year 2012 project milestone established for this research effort, and how INL's accomplishment of that milestone is not only central to the success of the LWRS program, but central to the continued safe and efficient operation of existing NPPs in the U.S. Specifically, the INL had the milestone of installing a digital full-scope mockup of a conventional NPP control room. This report describes the installation of a utility simulator at the INL, and in the process of doing so, reiterates the challenges with and need for NPP control room modernization.

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ACRONYMS

ANS	American Nuclear Society
ANSI	American National Standards Institute
ATHEANA	A Technique for Human Event Analysis
CFR	Code of Federal Regulations
COL	Combined License
CP	Construction Permit
CRADA	Cooperative Research and Development Agreement
CSNI	Committee on the Safety of Nuclear Installations
DC	Design Certificate
DCS	Digital Control System
DOE	Department of Energy
EPRI	Electrical Power Research Institute
HAMMLab	Halden Man-Machine Laboratory
HD	High Definition
HERA	Human Event Repository and Analysis
HFE	Human Factors Engineering
HRA	Human Reliability analysis
HSI	Human System Interface
HSSL	Human System Simulation Laboratory
I&C	Instrumentation and Control
IAEA	International Atomic Energy Agency
INL	Idaho National Laboratory
ISV	Integrated System Validation
LWRS	Light Water Reactor Sustainability
MCRs	Main Control Rooms
NEA	Nuclear Energy Agency
NPPs	Nuclear Power Plants
NRC	Nuclear Regulation Commission
OECD	Organization for Economic Co-operation and Development
OL	Operating License
OPAS	Operator Performance Assessment Scale
OpEx	Operating Experience
R&D	Research and Development
SCADA	Supervisory Control and Data Acquisition
SGTR	Steam Generator Tube Rupture
SONGS	San Onofre Nuclear Generating Station
SRP	Standard Review Plan
TI	Touch Interface
TOP	Technical Opinion Paper
US	United States
VDU	Video Display Unit
WGHOF	Working Group on Human and Organization Factors

1. INTRODUCTION

1.1 Purpose of Report

This report addresses the acquisition of a utility training simulator for use in research at the Idaho National Laboratory (INL). While full-scope control room simulators exist at every United States (U.S.) nuclear power plant for training purposes, they are locked to the current largely analog hardware panels used by the plant. This hardwired configuration makes them unsuitable for reconfiguration such as would be required for developing and evaluating new digital technologies to be integrated in place of analog hardware. U.S. research simulators, which feature a significantly greater degree of reconfigurability, are limited to vendor installations. These simulators are proprietary in nature and use; moreover, they are often centered on developing control rooms for next-generation power plants rather than modernizing existing installed control rooms. Non-US research simulators tend to mirror training simulators—offering limited reconfigurability—or, like vendor simulators, center on next-generation control rooms.

The purpose of this research is to document background considerations and the buildout process of taking a training simulator from an existing nuclear power plant and locating it at a national laboratory research facility to be used specifically for control room modernization research. Much of this report centers on fundamental questions behind the use of the research simulator in support of control room modernization efforts:

- Chapter 2: Why is control room modernization necessary?
- Chapter 3: Why is a research simulator necessary for control room modernization?
- Chapter 3: What are the differences between a training and research simulator?
- Chapter 6: What are the uses of a research simulator?

Additional parts of the report, specifically Chapters 4 and 5 and the appendices, provide concrete details regarding the INL's successful installation of a training simulator for research purposes. It is important to note that these latter sections are not meant to provide a detailed blueprint of the simulator but rather to sketch the considerations necessary for the buildout and overview its current and planned form. Readers wishing for a more comprehensive engineering discussion of control room simulators are encouraged to consult with simulator vendors mentioned throughout this report. The primary purpose of this report is to help readers understand why a research simulator is important for the U.S. nuclear industry and how the INL is deploying such a simulator.

1.2 Light Water Reactor Sustainability Program

Nuclear power accounts for 20-25% of current base load electricity generation in the U.S. (Nuclear Regulatory Commission (NRC), 2008) yet, replacement technologies including renewable energy or new plants have been slow to materialize. Without suitable replacements in place or in planning, it is imperative to ensure the continued safe supply of electricity through the current fleet of power reactors. The Light Water Reactor Sustainability (LWRS) Program is a research, development, and deployment program sponsored by the United States Department of Energy (DOE). The program is operated in close collaboration with industry research and development (R&D) programs to provide the technical foundations for licensing and managing the long-term, safe, and economical operation of nuclear power plants (NPPs) that are currently in operation. In short, the LWRS program focuses on research that contributes to the national policy objectives of energy and environmental security.

One of five principal R&D pathways addressing the Strategic Program Goals of the LWRS Program is *Advanced Instrumentation, Control, and Information Systems Technologies* (Halbert et al., 2009). The

strategic objective of this pathway is to establish a technical basis for new advanced instrumentation and control (I&C) technologies needed to achieve safety and reliability of operating nuclear assets. This is being achieved by carrying out an R&D program that is developing scientific knowledge as a necessary first step in implementing new technologies in nuclear energy systems. That is, advanced I&C technologies are needed to support the safe and reliable production of power from nuclear energy systems during sustained periods of operation up to and beyond their expected licensed lifetime. This requires developing new capabilities to achieve process control and implementing them in existing nuclear assets. It also requires developing and substantiating optimal approaches to achieve sustainability of I&C systems throughout the period of extended operation. To meet these requirements, R&D must be conducted on new methods for visualization, integration, and information use to enhance operator state awareness and leverage expertise to achieve safer, more readily available electricity generation, which includes new or enhanced control systems.

Given this need for I&C R&D, the LWRS Program is working closely with nuclear utilities to develop I&C technologies and solutions to help ensure the safe life extension of current reactors. One of the main areas of focus is control room modernization. While many utilities in nuclear industry have performed upgrades to their I&C systems, including safety significant systems such as reactor protection, very few higher risk/higher reward modernization efforts have been undertaken. This is due, in part, to a utility's need to meet electricity productions goals and the fact that their control room cannot be taken out of service for a long period of time for modernization. To embark on higher risk/higher reward modernization efforts, and achieve significant advances in plant performance, safety, and reliability, there is a clear need for a high fidelity, reconfigurable R&D control room simulator. A reconfigurable control room simulator will allow utilities to conduct the R&D needed to determine how to perform large scale modernizations of their control rooms. The INL is meeting this need by developing a multi-use reconfigurable control room simulator. With this simulator capability, the INL serves as a neutral test bed to develop and test the implementation of new digital control room system technologies, and is a key resource for testing emerging technologies for their application in nuclear power plant control rooms.

1.3 The Need for Large Scale Control Room Modernization

Commercial NPPs in the U.S. need to modernize their main control rooms (MCRs). Many NPPs have completed partial upgrades, but none of the 104 commercial reactors in the U.S. have completed a full control room modernization effort. Existing control rooms are almost entirely analog, hardwired, and manually operated control systems. Since analog technologies are no longer readily available, digital control systems are the required replacement systems for modernization. As noted by Thomas (2011), the nuclear industry has typically taken the approach of performing one-for-one replacements, whereby the new digital systems are customized for backwards compatibility with legacy systems. While this approach works, and configuration control is maintained on systems, this approach does not take full advantage of the enhanced capabilities of the new digital technologies. It is clear, however, that most utilities have assessed the risks and rewards of a "complete overhaul" modernization approach, and have decided to forego such extensive modernization, as that approach would likely be very costly given the need to integrate new technology with legacy systems, and would likely be the trigger for additional costs that propagate to other business areas, including training, qualifications, maintenance and licensing.

The LWRS R&D program is designed to mitigate the risk that industry faces from large scale control room modernization by providing a reconfigurable research simulator that can be used to test advanced I&C concepts. In doing so, industry can take advantage of the enhanced capabilities of digital systems beyond plant control and protection functions, including better support for automating work processes, improved error detection and correction capabilities, and greater situation awareness through advanced visualization technologies. The end result for the industry is lower operational costs while at the same time improving plant performance, safety, and reliability.

1.4 The LWRS Control Room Modernization Demonstration Project

Current analog control rooms are, in some cases, nearing the end of their service life, and it is difficult for utilities to obtain replacement parts. Industry must safely and smoothly transition to digital control room interfaces. As technologies are introduced that change the operation of the plant, the LWRS project can help identify their best advanced uses and help demonstrate the safety of these technologies. This research needs to be definitive and timely due to the rigor and duration of the regulatory review process. Also, early testing of operator performance given these emerging technologies will ensure the safety and usability of systems prior to large-scale deployment and costly verification and validation at the plant.

Such early system and operator performance testing is being done at the INL in a reconfigurable simulator. The INL is developing the state-of-the-art Human System Simulation Laboratory (HSSL; Hugo, 2012). At the heart of the HSSL is a reconfigurable control room simulator that can be used to develop and test the implementation of newer, digital control room systems. Further, the INL is procuring a set of touch screen simulator panels that can be configured to represent a current control room or one that incorporates various digital modifications. These simulators and the HSSL can serve as a key resource for testing emerging technologies for their application in nuclear power plant control rooms. In addition to the hardware and software capabilities, the INL's expertise in human factors and human performance metrics is being used to evaluate operator-in-the-loop alternatives being simulated.

Having the HSSL is a significant advancement and greatly enhances the capabilities for the DOE to support utilities in their efforts to carry out control room modernizations. The DOE LWRS Program is specifically addressing the need for a control room simulator through two program milestones in Fiscal Year 2012. These are:

1. Complete a digital full-scale mockup of a conventional nuclear power plant control room (due June 29, 2012).
2. Purchase new instrumentation and control information technology equipment for the HSSL (due September 30, 2012).

The report chronicles background and efforts associated with completion of the first milestone, which includes installation of utility simulator at the INL's HSSL facility. Note that the buildout of the simulator to support control room modernization may be considered as multiple phases, corresponding to the two milestones this fiscal year and future development efforts. The first phase, covered by this report, encompasses the acquisition of a fully functional, full-scope, reconfigurable MCR simulator in cooperation with a U.S. nuclear utility. The second phase, to be completed in September, 2012, includes the acquisition of additional simulator equipment that allows the optimized display of mimic panels for full-scale display and testing. The first phase of the simulator buildout consists of building the infrastructure to support acquisition of the commercial simulator software and plant-specific simulator model, whereas the second phase will consist of the acquisition of additional hardware that allows authentic operator interaction with the hardware panels that typify current nuclear control rooms. A supplemental report to the current volume is planned to document the second phase of simulator development. As additional plant models, panel hardware, or other facets of the HSSL are acquired or developed, these will likewise be documented.

A summary of the characteristics of Phases 1 and 2 are found below in Table 1. The details of the successful completion of the Phase 1 milestone are explained in further detail throughout the body of this report, along with supplemental information to give context to the importance and uses of the utility simulator for research applications. Specifically, Section 2 discusses the challenges of control room modernization as currently confronting U.S. utilities. Section 3 makes the case for the use of a utility

simulator for training purposes. Section 4 reviews the requirements for the simulator buildout in the first and second phases of this project. Section 5 introduces the simulator in the context of the HSSL, and Section 6 outlines research plans for the simulator.

Table 1. Phases of the HSSL Buildout

	Phase 1 (June 2012)	**Phase 2 (September 2012)**
Simulator Platform	L-3 Mapps Orchid Instructor Station	L-3 Mapps Orchid Touch Interface
Plant Model	San Onofre Nuclear Generating Station, Unit 2	San Onofre Nuclear Generating Station, Unit 2
Computer Graphics	114 Operator Workstation Displays	L-3 Mapps updated OneWorld panel graphics
Computer Hardware	Three Windows XP-based computers, including one server and two clients, with six accompanying high-definition displays	Six bays, each with three glass top touchscreen panels, connected to Phase 1 simulator server

2. THE CHALLENGES OF CONTROL ROOM MODERNIZATION

2.1.1 Technological Considerations

There are significant and unique hurdles in adopting new technologies as part of a MCR modernization strategy in NPPs. For example, in the course of analog-to-digital upgrades, it is first necessary to focus on the I&C, and develop a digital backend in which sensors and controls are digitized on a supervisory control and data acquisition (SCADA) system. Once it is possible to monitor and control the plant digitally (with potential redundant analog and mechanical backup I&C), the MCR Human System Interface (HSI) can be addressed. Though challenging to implement, digital technologies introduce the opportunity for new functionality in the form of advanced displays and automated or soft controls.

Additionally, although there is operating experience (OpEx) with digital technologies in other safety critical process control environments, advanced digital I&C is largely untested in the MCRs of NPPs. There are unique challenges to NPPs, including the close proximity of the MCR to the actual plant, which makes it difficult even to find adequate space to stage the components of a replacement control room. Additionally, the short outage windows of the plants require rapid change out of components in order to maintain targeted production levels for each plant. In many cases there may be no readily available commercial I&C solutions that generalize from other industries to meet the requirements of nuclear power plants. The one-of-a-kind nature of many NPPs further requires extensive customization by vendors.

A considerable amount of research, including O'Hara (2003), Pirus (2003), Woods (1995), and Hollan et al. (2000), also shows that numerous I&C, HSI, and human factors challenges must be, and can be, addressed in any MCR modernization effort. Typical challenges that are introduced by MCR modernization include: the small display space for information presentation introduces a keyhole or "tunnel vision" effect in operators (Pirus, 2003); soft controls increase secondary tasks (O'Hara, 2003; Pirus, 2003); increased understanding of automatic functions is required (O'Hara, 2003); and soft controls require conscious development of co-operation and communications practice to avoid breakdowns in threeway communications (Woods, 1995).

Operator concerns related to the number of visual display units (VDU) are examined in (O'Hara et al., 2001). The paper presents technical and historical reasons for this concern and its implication in the design of complex HSIs. Some of the concerns highlighted include a lack of communication between display designer and operators, difficulty in determining the appropriate amount of information to be displayed, and addressing the trade-off between task relevant displays and data-dense displays.

Salo et al. (2006) describe the operator's experience working in a screen-based control room (i.e., sit-down operator workstations vs. traditional stand-up panels). Interviews were conducted at four conventional power plants and one NPP, and involved operators with less than two years work-experience and operators with more than 20 years experience at both types of plants. Some of the major differences between conventional and nuclear power plants in terms of the digitalization of the HSI were presented. Salo et al. (2006) found that older NPP operators are more uncertain in using soft controls when performing operations than younger operators, and required more training. Additional operator concerns regarding differences associated with working in screen-based control rooms were expressed during the interviews, which were consistent with findings from other studies. These concerns included:

- How situational understanding of the process state is acquired (Salo et al., 2006; Lee et al., 2004)
- The effects of the increased level of automation on situation awareness (O'Hara et al., 2002)

- How general process knowledge through the new screens is acquired and maintained
- Learning how to navigate and perform operations using the screens
- The effect of screens on communication and coordination, and roles and responsibilities (Vincente et al., 2001)
- Learning the new system and training (Roth et al., 2002)

It is also interesting to note that the operators in Salo et al. (2006) expressed similar concerns that were documented in Roth et al. (2002) regarding their lack of experience and involvement in modernization processes, suggesting that the changes made through the modernization should be sufficiently operator-oriented.

In short, the commercial nuclear power industry is well aware of the need to modernize their MCRs and, based on their own operational experience and research, are well aware of the I&C and HSI challenges that must be overcome, including: the increased amount of data available to the operators, the usage and integration of soft controls and VDUs, the effects of increasing automation of systems, the effects of modernization on communication and coordination among operators and concepts of operation (e.g., roles and responsibilities), and the requirements for increased operator training.

2.1.2 Regulatory Considerations

There are additional regulatory considerations in MCR modernization. New functionality gained through digital modernization may go beyond the current licensing basis of plants and require significant licensing amendments. The U.S. Nuclear Regulatory Commission staff primarily uses the guidance in Chapter 18, "Human Factors Engineering" of NUREG-0800, *Standard Review Plan* (SRP) (1987), to review new plant design and modifications of existing control rooms. Though the SRP is the primary review tool used by the staff, it also refers to other significant review documents, e.g., NUREG-0711, *Human Factors Engineering Program Review Model* (2004), NUREG-0700, *Human-System Interface Design Review Guidelines* (2002); and NUREG-1764, *Guidance for the Review of Changes to Human Actions* (2007). If the MCR modernization effort leads to a significant change to any one of a number of areas, including but not limited to: function allocation, HSI design, staffing and qualifications, then the NPPs operating license may need to be amended, which could be viewed as additional cost and risk the utility must mitigate.

The NRC is the organization responsible for the review of human performance. It reviews the Human Factors Engineering (HFE) programs of applicants (e.g., for a construction permit (CP); operating license (OL); standard design certification (DC); and combined license (COL)) and licensees (e.g., for modifications and changes to a licensee's design or licensing basis). The purpose of these reviews is to improve safety by verifying that acceptable HFE practices and guidelines are incorporated into the plant's design. The guidance provided in this document, and in the supporting documents referenced, is used to conduct these HFE reviews.

Chapter 18 of the SRP identifies twelve areas of review that are needed for successful integration of human characteristics and capabilities into nuclear power plant design. These areas of review include:

- HFE Program Management
- OpEx Review
- Functional Requirements Analysis and Function Allocation
- Task Analysis
- Staffing and Qualifications
- Human Reliability Analysis

- Procedure Development
- Training Program Development
- Human-System Interface Design
- Human Factors Verification and Validation
- Design Implementation
- Human Performance Monitoring

While the process defines 12 areas of review, not all may be applicable to reviewing a particular applicant's or licensee's HFE program, especially when it comes to reviewing HFE aspects of control room modifications and HFE aspects of modifications affecting risk-important human actions.

The NRC is currently in the process of revising NUREGs-0700 and 0711 and will revise Chapter 18 of NUREG-0800 shortly thereafter. The ongoing revisions are based on research that has been performed since 2002 in the nuclear arena and on feedback from user experience. There have been two significant documents that have been published in that time frame that point to the need for further research—NUREG/CR-6947, *Human Factors Considerations with Respect to Emerging Technology in Nuclear Power Plants* (O'Hara et al., 2008), and a 2011 Nuclear Energy Agency (NEA) Committee on the Safety of Nuclear Installations (CSNI) Working Group on Human and Organizational Factors (WGHOF) work report, *Summary of Survey and Workshop Results on Areas of Research in Human Factors for the Design and Operation of New Nuclear Plant Technology* (2012).

NUREG-6947 was sponsored by the NRC because of the increased use of automation and other technologies in existing, new, and advanced nuclear power plant designs that has the potential to introduce new HFE challenges (O'Hara et al., 2008). Sixty-four potential human performance research issues associated with the introduction of emerging technologies in nuclear power plants were identified. These potential research issues are organized into seven high-level topic areas:

- Roles of personnel and automation
- Staffing and training
- Normal operations management
- Disturbance and emergency management
- Maintenance and change management
- Plant design and construction
- Human factors engineering methods and tools

The impetus for the WGHOF work report (2012) grew out of an NEA CSNI WGHOF Technical Opinion Paper (TOP), titled *Research on Human Factors in New Nuclear Plant Technology*, which identified eight broad topic areas that warrant further research:

- OpEx from New and Modernized Plants
- Evolving Concepts for the Operation of Nuclear Power Plants
- The Role of Automation and Personnel: New Concepts of Teamwork in Advanced Systems
- Management of Unplanned, Unanticipated Events
- Human System Interface Design Principles for Supporting Operator Cognitive Functions
- Complexity Issues in Advanced Systems
- Organizational Factors – Safety Culture
- HFE Methods and Tools

The work report expanded on these topics by suggesting specific research efforts, potential collaborations, and identified research facilities at which the research could be performed.

The WGHOF work report (2012) is important because the nuclear community is currently at a stage where existing reactor control stations are undergoing various forms of modernization, new reactors are being built in many countries with screen-based control rooms, and advanced reactors are being designed through international cooperation to support future power generation. With the introduction of advanced plants, there will be new reactor and system designs, new tools to support plant personnel, and changes to NPP staffing configurations. The concepts of operation and maintenance requirements for this new generation of plants are likely to be quite different from those employed in today's plants. It is important that the potential impact of these developments is evaluated and understood by prospective operators and regulators responsible for determining the acceptability of new designs to support human performance in maintaining plant safety.

Many of these new designs will also prove relevant in upgrading MCRs of existing plants. The introduction of new technology is viewed as having promise for improving the safe and efficient operation of existing NPPs. To ensure the appropriate application of technology to support human performance and plant safety, it is important to evaluate the technological advances in terms of both potential negative and positive effects. The research described can provide the technical basis to help ensure that the benefits of new technology are realized and that the potential negative effects are minimized.

Based on the results of these latter two efforts (O'Hara et al., 2008; WGHOF, 2012) there has been a significant amount of new research identified that needs to be done to both support regulatory reviews but also to improve the safety and efficiency of nuclear power. The need for MCR modernization serves as a strong motivator to update regulatory guidance and to conduct research that supports both regulator and industry needs.

However, utilities must also decide the extent of modernization that is desired and needed to prioritize the process by which they will achieve that modernization. The plant's end state vision outlines both the extent of digital upgrades and the course of deployment. For example, a utility may decide to keep its existing panel-based control room and phase in digital control system (DCS) displays to replace aging analog I&C. Another utility may decide to adopt a complete control room update—doing away with panels completely and moving toward soft controls and plant overview displays at local operator workstations. Yet a third strategy might use a graded approach in which the utility plans for introduction of a DCS backend in the short-term with an eventual goal of introducing a completely new control room concept as part of long-term plant sustainability.

2.1.3 Utility Modernization Strategies

Given the various possible end state visions for control room modernization, a survey was developed to obtain the commercial nuclear utility's perspective on NPP MCR modernization. The survey was issued during the 2012 Winter LWRS Utility Working Group Meeting, held March 13-15, 2012, in Phoenix, Arizona. As seen in Figure 1, the results showed that, with respect to the main drivers of MCR modernization, 55% of people affiliated with utilities believe that improving performance, safety, and reliability is the main driver, and 45% believe avoiding obsolescence was the main driver. Other drivers such as reduced costs through staffing reductions, and enhanced functionality received no votes from utility representatives.

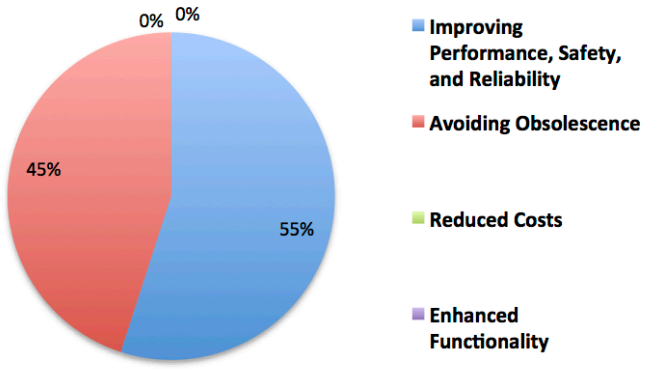

Figure 1. Main Drivers for MCR Modernization

With respect to the main barriers to MCR modernization, the survey showed that 50% of utility respondents believe that cost is the main barrier. Twenty percent of utility respondents believe a lack of an end state vision is the main barrier. Another 20% believe the regulatory approval process is the main barrier, and 10% believe the lack of process expertise and operational experience is the main barrier. See Figure 2.

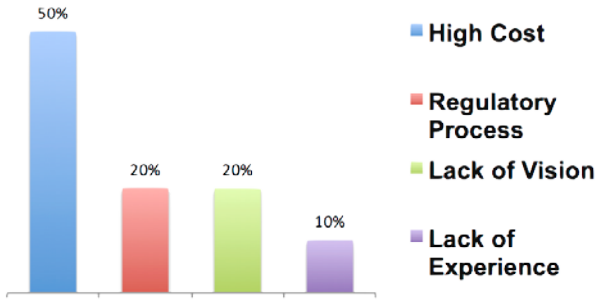

Figure 2. Main Barriers for MCR Modernization

The next section of questions on the survey asked respondents to evaluate different approaches or types of modernization across a number of different evaluative dimensions. The types of modernization were: 1) Piecemeal (i.e., where individual pieces of equipment are replaced over time), 2) Partially modernized I&C and Human System Interfaces (HSI), 3) Behind-the-boards modernization (of I&C only), 4) Fully modernized I&C and HSI, and 5) None of the above. Two of the key evaluative dimensions included which type of modernization utilities preferred, and what they thought was most likely to be adopted at their utility.

As Figures 3 and 4 show, utility representatives reported that they preferred the fully modernized I&C and HSI approach to MCR modernization, but also indicated that the partially modernized I&C and HSI approach was the most likely to be implemented.

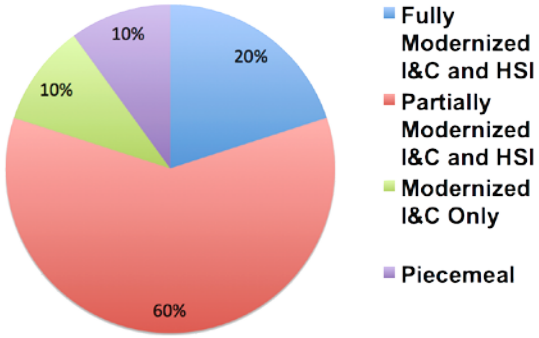

Figure 3. Preferred Modernization Approach

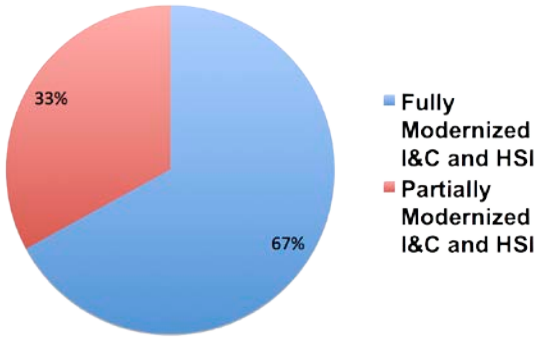

Figure 4. Likely Modernization Approach

Questions were also asked about the extent to which utilities plan to use various technologies in their MCR modernization efforts. The overall trend showed that most utilities plan to use a number of "new" technologies extensively, versus not at all, or in a limited fashion. The only exceptions to this trend were the planned use of workstations (i.e., computers with displays often configured on a desk with operators sitting), and panels (i.e., controls and displays that are often arranged in a rack or upright configuration with operators standing). In these cases, a high percentage of utility respondents indicated they were not sure to what extent their plans for MCR modernization would include these technologies. Table 2 provides a summary of these results.

Broadly speaking, the results show there is general consensus among utilities regarding the need to modernize, (i.e., there are valid drivers), but that there is significant divergence with respect to how modernization will occur, and what approaches and technologies will likely be used. This finding is consistent with the idea that all utilities need to develop their own end state vision for modernization, as it is clear that a one-size-fits-all end state vision will not work well for NPP MCR modernization.

Table 2. Plans for Using Various Kinds of Technologies in MCR Modernization

	No plans	Limited use	Extensive use	Not sure	Not applicable
Workstations	0%	11%	44%	44%	0%
Panels	0%	30%	40%	30%	0%
Soft Controls	0%	30%	60%	10%	0%
Advanced Diagnostics	10%	40%	40%	10%	0%
Intelligent Alarms	0%	20%	70%	10%	0%
Overview Displays	10%	10%	70%	10%	0%
Computerized Procedures	10%	30%	50%	0%	10%
Automated Controls	11%	33%	44%	11%	0%
Operator Aids	0%	20%	70%	10%	0%
Technologies and integrate CR and Balance of Plant information	0%	30%	60%	10%	0%

It is also worth pointing out that a group of researchers were also given the same survey, and the survey identified differences between researchers and utilities, which highlights the potential for disparity in translating utility needs into research to support modernization. Identifying such differences serves to help avoid pitfalls a priori as researchers and utilities work together. The survey results are a helpful starting point for more effective collaboration, whereby industry identifies its MCR objectives, and researchers respond with effectively targeted R&D using the HSSL reconfigurable control room simulator. Future work will refine this industry vision and identify milestones and processes by which LWRS research can help utilities achieve their end state vision.

3. THE NEED FOR RESEARCH SIMULATORS

3.1 The Emergence of Training Simulators

A 2004 report by the International Atomic Energy Agency (IAEA) highlights the historic development of training simulators. Beginning in the 1970s, computerized control room simulators were put in place at centralized facilities to help train control room operators. These simulators were limited by a lack of fidelity in terms of control panel layouts and underlying thermal hydraulic code, making them useful for teaching basic plant principles to operators but less useful for plant-specific training. By the 1980s, the fidelity and availability of simulators was greatly increased, and by the 1990s, it became the norm internationally for each plant to have a high-fidelity plant-specific simulator. In the U.S., the requirement for a plant simulator is outlined in 10 *Code of Federal Regulations* (CFR) Part 50 (US Office of the Federal Register, 2009), Paragraphs 55.45(a) and (b), in terms of operator licensing. A licensed operator must demonstrate competence during a plant walk-through and on a simulator. In fact, since 1981, the U.S. NRC Regulatory Guide 1.149, *Nuclear Power Plant Simulation Facilities for Use in Operator Training and License Examinations* (2001), has endorsed ANSI/ANS-3.5, *Nuclear Power Plant Simulators for Use in Operator Training* (1998), which requires a plant-specific simulator facility for use in training.
The IAEA (2003) defines different types of plant simulators. These include:

- *Basic principles simulator*—which provides a simulation of general concepts relevant to the operation of a plant without providing a faithful mockup of a specific plant
- *Full-scope simulator*—which is a faithful replica of a specific plant control room and its operations
- *Other-than-full-scope control room simulator*—which closely mimics a plant but deviates from its human-machine interface
- *Part-task simulator*—which only models specific systems of a plant

As used in this report, the term, *plant training simulator*, is synonymous with *full-scope simulator*. All simulator types may be used as part of an effective training regime, but there has been increased emphasis on and requirements for training in full-scope simulators. The considerable demand on plant training simulators was already evident in 1992, when a survey conducted by the Institute of Nuclear Power Operators suggested that single-reactor site training simulators were used an average of 2000 hours annually across two daily shifts. Double and triple reactor sites saw an even greater utilization of their simulator facilities.

3.2 The Emergence of Research Simulators

Early control room studies tended to focus on vary narrowly defined parameters such as the relationship between time available and the reliability of the operators (Swan & Guttman, 1983). These studies could generally make use of basic principles simulators. Gradually, the complexity of simulator studies increased, reflecting the need for more sophisticated crew understanding by human factors and human reliability researchers. For example, advanced studies of time-reliability (Spurgin et al., 1989), studies of operator cognition (Roth, Mumaw, & Lewis, 1994), validation of human reliability methods (Gore et al., 1995), studies of situational awareness (Hallbert, 1997), and studies to understand human error mechanisms (Drøivoldsmo, 2000) required much more complex simulator facilities. In part, these were conducted in the plant's full-scope simulators. Additionally, dedicated research simulators were devised, e.g., the Halden Man-Machine Laboratory (HAMMLab) at the Halden Reactor Project in Norway in 1983 (Øwre, 2008).

HAMMLab, across its three versions, has offered a high-fidelity simulator facility in which the simulator is functionally linked to a specific plant but in which the human-machine interface may differ from that found in the plant. Typically, HAMMLab incorporates more advanced digital instrumentation and controls than the plant. As such, HAMMLab can be called an *other-than-full-scope control room simulator* in IAEA parlance due to its considerable interface flexibility. HAMMLab remains the fullest-scope reconfigurable control room simulator for nuclear research purposes, although plant vendors have developed similarly sophisticated simulators for development of advanced and next-generation plant human-machine interfaces.

3.3 The Ongoing Need for Full-Scope Simulators

3.3.1 U.S. Research Questions

The need for full-scope simulators in research has not subsided. Several U.S. partners—the U.S. NRC, the Electrical Power Research Institute (EPRI), Sandia National Laboratories, and Idaho National Laboratory—as well as international members of the Halden Project, have been working with Halden Reactor Project to run control room simulator studies. These studies, which use crews from Scandinavian plants, are used to determine crew behavior in a variety of normal and off-normal plant operations. The findings are ultimately used to guide safety considerations at plants and to inform human factors and human reliability analysis (HRA)—both at the regulator and in industry.

For example, a recent study (Lois et al., 2008) used HAMMLab crew performance data on a simulated steam generator tube rupture (SGTR) scenario to offer a baseline of crew performance against which a variety of HRA methods can be benchmarked. Each HRA method is predicated on different qualitative models of human error, and each HRA method ultimately features a slightly different quantification approach to generate human error probabilities. Using 14 crews across easy and complex variants of the SGTR scenario, the HAMMLab simulator enabled Halden researchers to document a variety of factors that contributed to crew success and—in a few cases—crew difficulty while isolating the steam generator. These operational performance data are incomparable as a basis for validating the predictions from various HRA methods.

In due deference to the accomplishments of the HAMMLab, there has recently been a strong desire to have access to similar control room research facilities in the U.S. Many of the large scale U.S.-based control room studies now date back 15 or more years, while the need for crew performance data has continued. In the absence of U.S. simulator studies, new models of human reliability, including the second-generation HRA methods (U.S. NRC, 2000) like A Technique for Human Event Analysis (ATHEANA) (U.S. NRC, 2000; Forester et al., 2007) have come of age, highlighting the need for a better understanding of cognition and context in crew activities. In this same time frame, there has been increased awareness of errors of commission (e.g., incorrectly disengaging an automated system) as major factors on crew performance, whereas earlier research was centered on errors of omission (Organization for Economic Co-operation and Development (OECD) NEA, 2002). There has been a significant increase in the awareness of the importance of safety culture to plants (IAEA, 2002). There has been the emergence of a popular and significant new approach to safety called *resilience engineering* (Hollnagel, Woods, & Leveson, 2006). Finally, there have been significant technological advances, both to human-machine interfaces (e.g., digital control rooms, automation, or computerized procedures (Boring et al., 2008)) and to the types of plants being built. Perhaps most importantly, there has been what has been called the nuclear renaissance (Nuttall, 2005), or the prospect of new plant builds in the U.S. that utilize advanced plant designs, many of which require different control room crew activities than the current generation of plants. Many of the same control room technologies found in new builds are finding their way into existing plants through modernization efforts, and there exists no readily available facility to engage new designs through a rigorous verification and validation process in order to ensure new technologies are as safe or safer than existing control room technologies.

3.3.2 Limitations of Dedicated Research Simulators

Certainly, it is possible to use HAMMLab to address many of these issues. But, there are certain reasonable limitations in using HAMMLab. The primary limitation of the HAMMLab is the generalizability of the results:

- *Generalizability of the control room.* The Halden facilities are research oriented. The human-machine interface is not a direct replica of a specific physical plant but rather a functional equivalent. There is evidence to suggest that simulators that are functionally similar will generate comparable results to each other (Stanton, 1996). However, due to the lack of comparable plant-specific simulators for research, it has not been possible to validate all HAMMLab findings as extensively as Halden researchers might like. Much of the human-machine interface technology used at Halden is cutting-edge and is not part of standard plant control rooms yet. For example, the HAMMLab control room is all digital, featuring large overview displays, window and menu-based controls, and scrolling alarm lists instead of annunciator displays. These features optimize the HAMMLab simulator for testing and improving new control room technologies, but they can introduce subtle differences between the simulator and the actual plant.
- *Generalizability of the crews.* In part, there are differences in operational culture that may make it difficult to generalize the results from international crews back to U.S. crews. For example, the Thirty Minute Rule (IAEA, 1980) may be interpreted to mean the right actions should be *decided* in 30 minutes, whereas in the U.S. actions are interpreted to be *completed* within 30 minutes. This distinction comes into play with advanced computerized support systems in some international plants, which automatically initiate most primary activities within 30 minutes (Büttner, 1985), necessarily restricting operator actions during this period. The control systems used at current generation Scandinavian plants do not exhibit substantially more automation than U.S. plants. Thus, this difference in operational culture is unlikely to manifest in HAMMLab studies, but other operational culture differences are poorly understood and even more poorly documented. HAMMLab, in tandem with U.S. plant studies, offers the ideal test bed for studying such differences to the extent they exist.

Clearly, from a U.S. perspective, it is desirable to work with HAMMLab to replicate findings and generalize to U.S. crews. Still, there is no current general-purpose U.S. research simulator facility comparable to HAMMLab. This does not, however, mean there is a shortage of simulator facilities in the U.S. As already mentioned, vendors have proprietary simulators used in research and development. And, the U.S. NRC and industry maintain training simulators, including the facilities used by each plant to train and re-qualify operating crews. The time is right to reconsider the use of such training simulators for research.

3.4 Using Training Simulators for Research

3.4.1 Framework for Research Studies at U.S. Training Simulators

The cost and time to build a new dedicated research simulator in the U.S. is prohibitive. Moreover, such a facility may not serve the interim needs of documenting crew performance in the current generation of plant control rooms. The solution proposed here is for studies similar to those performed at HAMMLab to be replicated in the U.S. at plant-specific training simulators.

Dedicated research simulators are actually quite similar to training simulators at their core. While the specific human-machine interface of the research simulator may be cutting-edge, the simulation controller is commercially available. The same level of control over the simulated plant conditions is generally available in a training simulator as in a research simulator. The key difference is that the training

simulator is not designed to collect the crew performance data that are typically gathered in a research simulator.

This report proposes securing training simulators from current plants in dedicated research facilities to obtain crew performance data similar to those obtained in a dedicated research simulator. The transplanted simulator represents a high fidelity replication of the actual environment, allowing realistic and naturalistic data collection of operator performance. In this framework, the researcher works in tandem with the simulator trainers to:

- *Devise realistic scenarios that can be run on the simulator*. For example, an SGTR scenario might be devised similar to the one in Lois et al. (2008), with specific variants such as misleading indicators on the relief valve closure status. These scenarios may represent well trained scenarios (for which we seek good crew baseline data) or extremely unlikely scenarios that may challenge crews. All scenarios should, of course, be reviewed and approved by applicable ethics review boards. Scenarios may be *part-task* (interrupted at the completion of specific operations) or *full-trial* (allowing the full scenario progression and accompanying crew responses).
- *Determine the crew behaviors to be measured and the appropriate way to gather these data.* Common nonintrusive measures may include videotaping, simulator logs, and observer note-taking from the control booth. It is useful to have plant experts present to provide commentary on crew actions and sometimes to provide performance ratings according to predefined scales such as the Operator Performance Assessment Scale (OPAS) (Skraaning, 1998). For observers, it is usually necessary to have a complete set of procedures on-hand to document how the crew steps through the procedures. In some cases, it may be appropriate to discuss crew actions with the crews as part of the standard post-run debriefing. At that time, it may also be desirable to present short questionnaires to allow the crew to self-identify any aspects of the scenario that caused them difficulty.

In keeping with standard research practice involving human test participants, it is important to maintain the absolute anonymity of the crews. All crews' data and performance logs should be kept anonymous to prevent linking performance back to specific crews. Findings from the studies should be presented as aggregate findings, delivered as specific data to inform human reliability and human factors studies or in the form of general lessons learned to aid trainers in future training exercises. In most cases, even the specific plant should not be linked to findings, and never without plant approval. Since simulator studies may involve unusual scenarios that are not well-trained, it should be guaranteed that there will never be any negative repercussions in the unlikely event of poor crew performance. Simulator research studies should be treated positively, strictly as a learning exercise. Moreover, performance during research studies is not appropriate as part of operator re-qualification examination.

It is important to note that simulator research studies are equally interested in performance success as performance issues. Successful human actions are currently under-examined. It is not possible to form a complete picture of crew operations just by reflecting on human errors. Thus, an equally important component of human factors and human reliability research should be to investigate everyday good crew performance, which has not been an emphasis in the past. For evaluation of new control room interface elements, it is important to document positive metrics (e.g., successful performance, high operator situation awareness, and high operator satisfaction) in addition to any shortcomings revealed in the operator interaction with the system.

In most cases, it will not be necessary to run the full complement of crews at the plant. Evidence suggests that approximately 85% of possible errors can be captured by five participant groups (or crews, in this case) (Nielsen & Landauer, 1993; Boring, 2006). Most studies would seek to use a subset of plant crews in training scenarios. These scenarios may be linked to existing training requirements or, resources permitting, may be specific scenarios developed for particular research purposes.

3.4.2 Advantages

Participation in simulator research studies affords industry and the regulator a unique opportunity to investigate factors affecting crew performance in current control rooms and to compare that performance to performance on modernized interface elements in the control room. Practically speaking, over time, such studies may be used to develop new industry best practices and to improve crew preparedness for unusual plant events. From a research perspective, findings from training simulator studies may inform new or improved interfaces or be used to develop a more realistic representation of normal crew performance. Such research will ultimately drive recommendations for the implementation of next-generation control room interfaces based on principles of crew performance in current control rooms.

3.5 The Complementary Nature of Research and Training Simulators

3.5.1 Limitations of Training Simulators

There is ample room for the coexistence of dedicated research and training simulators in research studies. The differences are centered on the types of studies and the types of data that are the aim of the studies. Where the aim is to collect human performance information from actual crews in current control room configurations, the training simulator offers a logical first step. But, the limitations of training simulators must be understood:

- *Limited availability*. Training simulators have as their first priority the training of crews. Research studies may be scheduled as available, but they should not interfere with training exercises. For this reason, research studies that align closely with training tasks are those best suited for training simulators. Crews, trainers, and the simulator facility are limited commodities at the plant, and research studies should complement their primary purpose.
- *Simulator flexibility*. The flexibility to manipulate plant parameters and operational situations may be limited in the training simulator. For particular research questions related to crew performance, it may be desirable to configure the plant parameters in an unusual way (e.g., multiple simultaneous faults). While this level of control should be available in training simulators the same as in research simulators, the ease with which such manipulations can be made may be limited by the need to create readily configurable scenarios appropriate to training. As well, such configurations can be time-consuming to set up and may not be suitable for a simulator that serves double-duty for training exercises.
- *Limited data collection.* As noted, the ability to collect wide types of data is restricted. Primarily observational data may be collected, but advanced data collection techniques such as noted in Tran et al. (2007) are not easily or unobtrusively retrofitted to the training simulator.
- *Fixed human-machine interface*. Training simulators are purpose built to mimic the actual human-machine interface of a specific plant. As such, training simulators are not well suited for exploratory studies of novel control room interface elements. Training simulators may be suitable for implementation of equipment upgrades at the plant (e.g., phasing in new control panels and training crews prior to installation in the actual plant control room). They are not, however, generally suited for trying out new equipment.

3.5.2 Advantages of Research Simulators

The above limitations of training simulators for research illustrate the importance of maintaining and championing dedicated research facilities for control room simulation such as at HAMMLab. Dedicated research simulators are ideal for:

- *Scheduling flexibility*. Research simulators are generally not in as heavy of rotation for use as plant training simulators. Depending, of course, on the number of studies being conducted, it is possible to

schedule training simulators for longer periods of time and with greater scheduling flexibility, because they do not serve double duty for other purposes.

- *Configuration flexibility*. Research simulators offer maximum control over plant parameters and are not limited to a specific plant. In fact, research simulators may in many cases be reconfigured to different types of plants, including advanced plants that are still under development. For example, HAMMLab may be easily reconfigured to be a pressurized water reactor or boiling water reactor, not to mention functionally equivalent to specific plants within those plant types.
- *Data flexibility*. Research simulators may collect the same observational data as can be collected in training simulators. In addition, it is possible to configure the research simulator for advanced data collection like physiological measures and eye tracking (Øwre, 2008), requiring specialized equipment that is not easily retrofitted to training simulators.
- *Crew flexibility*. While training simulators are plant specific, research simulators may be reconfigured as needed. This reconfigurability makes it possible to study crews from different plants within the same study. The simulator may be reconfigured to match the home plant very closely, or a hybrid approach may be adopted, whereby crews operate on a generic plant that is similar to but not identical to their home plant. Studies involving different crews are important for understanding operational culture (Heimdal, 2007) —the plant or culture specific nuances that ultimately may impinge on crew performance. For example, it is important to understand if crews generally respond the same way to a plant upset. Even though the procedures may be identical, crew dynamics and even crew adherence to those procedures may be different enough to warrant plant localization of certain aspects of the procedures. Without comparative control room studies, the efficacy of localized procedures remains speculation. Moreover, without understanding differences in crews, the generalizability of research findings from one crew type to another may come into question.

3.6 Discussion

Simulator studies afford human factors and human reliability researchers a glimpse of control room crew activities in a natural setting. Strides in research simulators have allowed increasingly sophisticated insights into crew performance and have made it possible to test and refine novel human-machine interface elements prior to their implementation in advanced control rooms at plants. Still, there are limitations to research simulators—interface enhancements may cause the simulators to deviate from being true full-scope simulators and may prevent the findings from being fully generalizable to current plants. Moreover, a gap exists, in that dedicated research simulators are not readily available in the U.S., even though there is a need to study U.S. crew performance. This report highlights the opportunity now to conduct research studies using a plant training simulator reconfigured for research purposes.

4. CONTROL ROOM SIMULATOR BUILDOUT REQUIREMENTS

4.1 Requirements

To conduct MCR modernization research, a control room buildout based on the plant-specific full scope simulator is required. In this project, a pressurized water reactor full-scope simulator is used to mimic the actual control room operational scenarios. The following requirements were considered during build out:

1. Information Access and Navigation
2. High resolution and display clarity
3. Reconfigurability
4. Multiple operators

4.1.1 Information Access and Navigation

An overview of the plant control room layout shown in the simulator (see Figure 5), indicates that the control room has six front panels. Each panel corresponds to unique sets of control room operations and has unique sets of annunciator displays, analog controls, and analog gauges. There are multiple manners to display these six panels using digital displays (discussed in the next section). One of the important requirements is that an operator should have access to all the information displayed on different screens of different panels. In addition to information access, an operator must be quickly able to navigate to different controls presented on the digital display. This is specifically important when a malfunction occurs and alarms are activated. During a plant transient, specific procedures need to be followed to address the alarms and evolving scenarios, which require quick navigation to access controls across the different panels.

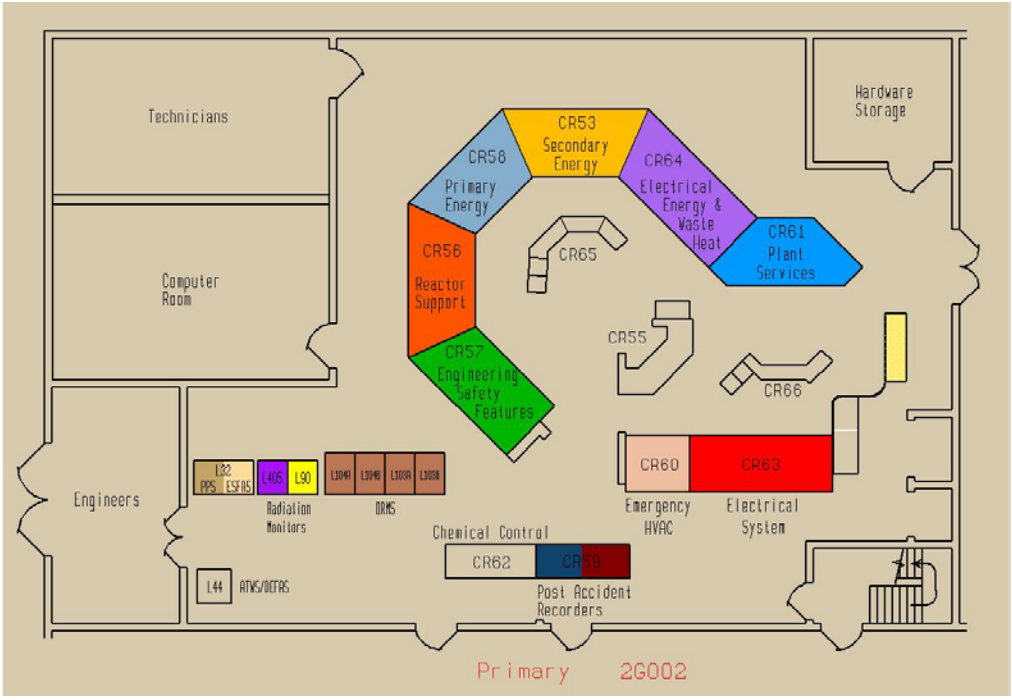

Figure 5. An Overview of the Panels Represented in the Main Control Room Simulator

4.1.2 High Resolution Displays

As an example, the panels displayed in Figure 5 can be broken into further displays. It is estimated that the control room simulator front panels in the present simulator require 114 separate screens to be rendered in the form provided in the engineering simulator. Literally thousands of gauges, controls, and annunciators must be represented digitally to achieve the full scale of the simulator. To obtain high fidelity display of graphics, text, and numeric values on different panels of the simulator, a high-resolution display is essential. A 1080p high-definition (HD) or better display with appropriate aspect ratio will provide the required quality of display. Also, the rendering technique used in the development of the simulator should feature anti-aliasing, allowing graphics to be rendered legibly on the display. The graphics should also be scalable, an effect best accomplished through vector-based rendering. It is estimated that using high-definition displays, it is possible to aggregate the 114 separate windows into a smaller number of displays. Each panel can be represented by a benchboard, horizontal, and upper display to achieve a faithful replica of the actual control room panels.

As well, with a suitable on-screen navigation scheme, it is possible to provide separate windows to represent each screen. The drawback of windows is that they do not provide the ability to see all relevant information at a glance, and important information may be located on non-visible windows. The need to toggle between windows increases both the time to locate and respond to relevant information and the amount of information the operator must hold in working memory. In part to address this deficiency, the present simulator features functionally grouped windows, thereby minimizing the need for the operator to navigate between several windows to locate particular transient information or control the plant relative to that transient. An example of the panel navigation between screens or windows is depicted in Figure 6.

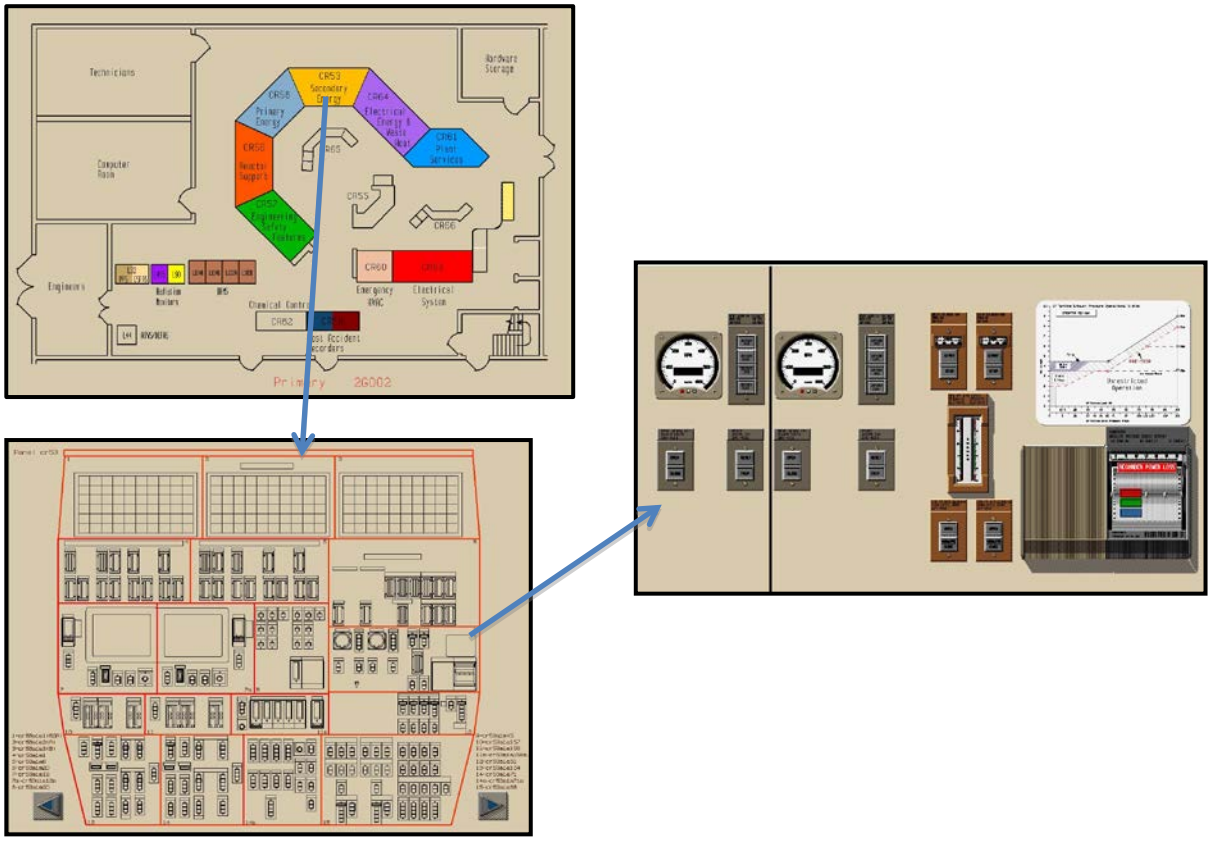

Figure 6. Navigation from the MCR to Panel to Individual Control Windows

4.1.3 Multiple Operators

In practice, more than one operator monitors and controls the operation of a nuclear reactor in a control room. Hence, the buildout to mimic the control room that can be used for training and examination purpose should be able to support multiple operators. In particular, each operator must be able to interact with the simulator controls independently. Such a requirement precludes some solutions such as projector based systems that use gyroscopic mice. The ability of the operator to go to any project screen using any mouse is not viable with current technology.

4.1.4 Reconfigurability and Upgradeability

Today, most NPP control rooms feature a layout based on a 1980s technology environment. With control room modernization gaining focus, the control room of the future will allow operators to have more and better data to work than ever before, and will have a broader range of options for control. The introduction of new instrumentation and controls capabilities into the current control room work environment poses significant challenges. In order to accommodate the future modernization needs into the current system, the present simulator system should be reconfigurable and upgradeable as per an evolving research focus. Control rooms are not static, and upgrades will likely feature a graded approach, whereby current analog technology is first replaced with digital equivalents. Only after the migration to digital will most control rooms begin the process of increasing the functionality afforded by the digital technology, including integrated displays and soft controls.

4.1.5 Possible Solutions

There is no single solution to the problem space associated with the simulator buildout to mimic the current control room. Each solution has its own advantages and limitations, which are discussed in this section. There are many factors (or constraints) that must be taken into consideration and influence the outcome of the solution. These include: cost, buildout space, hardware compatibility with current and future versions of the simulator, and flexibility (or expandability) to other plants' full-scope simulators.

4.2 Layout Configuration

Many possible control room layout configurations are possible. One of the most common layout configurations is the horseshoe configuration as shown in Figure 7. The realization of the configuration in Figure 7 or any other configuration can be achieved using different hardware alternatives such as:

1. A workstation-based solution,
2. A single large high-resolution display such as 65-inch TV display or projector,
3. Advanced Front-End HSI, and
4. Touchscreen "glass top" panels.

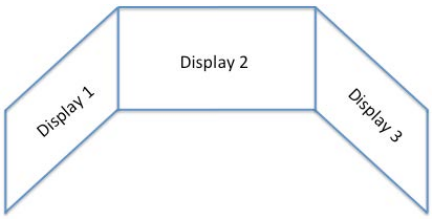

Figure 7. Horseshoe Control Room Layout

4.2.1 Workstation-Based Solution

Where space constraints are significant, it is possible to present panels piecemeal using VDUs. In this configuration, the panels are decomposed into subset screens or windows and displayed on a VDU. This

is the configuration often employed in industries like aviation, which use multifunction displays to allow the operator (or pilot, in this example) to toggle between relevant screens while maintaining a minimal overall footprint in the cockpit. The idea of a workstation-based display of multiple screens of information represents an ideal arrangement for part-task simulators, in which the operators can focus on a limited range of I&C during an operational scenario. It is also possible to use such part-task displays to operate the entire plant. The effect is akin to a flashlight shone in a darkened control room, whereby only a limited portion of the panels may be seen at one time. As noted previously in Section 4.1.2, this presentation limits the ability of the operator to see system status in the context of broader plant activities, since the operator must consciously navigate between windows or screens, inserting temporal delays and limiting mental binding of disparate elements of the plant represented across the breadth of the entire control room.

4.2.2 Single Large Display Unit

A high-resolution display or a projector-based system can be used as a single display unit to individually display each panel of the simulator. Six or more projectors can be configured to display all the panels of the simulator. There are, as noted, concerns with a projection-based system regarding interactivity of multiple operators, as well as the effect of shadows or obscured displays and projector resolution. However, interactive projector technology allows users to actively interact with the projected image. There are many vendors for interactive projectors and each allow different levels of interaction with the projected image with different interaction tools. The short-throw setup of most projectors, limited resolution, and the logistics of mounting six or more projectors are still major disadvantages.

4.2.3 Advanced Front-End HSI

As noted, the HAMMLAB features advanced HSIs, including large overview displays and highly customized individual operator workstation controls. ProcSee is a development tool by Halden Reactor Project for creating advanced process surveillance and control systems. ProcSee is particularly attractive to SCADA systems and simulator suppliers who can establish generic HSIs for easy adoption and configuration of their customer needs. HAMMLab, has developed their own configurable front-end graphics with dynamic behavior and end-user interface. The main advantage of a Halden ProcSee (or equivalent) front-end is that it is an attractive and flexible solution with runtime reconfigurability that can be used for the design of control rooms of the future. The limiting factors are that a Halden ProcSee front-end is next generational and does not closely mimic conventional control rooms. It could be designed to mimic a conventional control room, but the development efforts to create the mimic interface are significant, and the generalizability of findings to existing reactor control rooms might be severely limited.

4.2.4 Glass Top Panels

To allow operators to navigate between different panels and to avoid multiple keyboards and mice, digital displays with touch interfaces are a viable and desirable solution. Popularly known as touchscreen displays, such displays can be set up in number of ways to mimic any control room configuration. GSE Systems, Inc., L-3 MAPPS, and Western Services Corporation are the three leading vendors currently producing glass top control panels. Figure 8 shows one example, L-3 Communication MAPPS's Orchid Touch Interface (TI) bay. The bay allows high fidelity panel graphics to be displayed on large touch screen monitors with 1080p (full HD) resolution. The monitors are mounted on frames, known as a bay, and can be adapted to mimic different control room layout configurations. A single bay of Orchid TI can be used to navigate between different control panels in a simulator. Alternatively, several bays can be configured to represent all the control panels. Orchid TI is a complete solution as far as a control room

simulator buildout is concerned. In addition, Orchid TI is compatible with other full-scope plant simulators developed by L-3 Communication MAPPS. The authors, at the time of publication, are not aware of any plug-in in development that would allows Orchid TI to be compatible with the full-scope simulator developed by other vendors, which may prove a limiting factor in generalizing the utility of the hardware bays across other plants and utilities.

Figure 8. The L-3 Orchid Touch Inteface Bay

5. FROM PLANT TRAINER TO RESEARCH SIMULATOR

There exists no research simulator configured specifically to address the redesign of legacy control rooms in the U.S. nuclear industry. In light of this fact, the INL has undertaken the conversion of a legacy training simulator for use in control room modernization. Through a Cooperative Research and Development Agreement (CRADA) with a U.S. utility, the INL has acquired the software code corresponding to a specific NPP's engineering simulator. While only workstation-based displays are provided with the software, the front-end simulator at the actual plant consists of analog panels. There is limited utility in crafting a hardware replica of the analog panels found at a specific NPP. As such, the INL has reviewed ways to construct a full control room using digital-only technology, as noted in this report.

The INL is working with San Onofre Nuclear Generating Station to assist in their long-term control room modernization effort. Although the INL is supporting a primary partner in this effort, the objective is that lessons learned from working with SONGS may be disseminated as lessons learned to support the entire current fleet of reactors in the U.S. Process and interface findings will be shared with other utilities and the U.S. NRC in order to streamline the process by which utilities may modernize their current control rooms to help ensure the safe, sustainable operation of current reactors. SONGS, in cooperation with the simulator vendor, L-3, has made available a copy of the full-scope training simulator software used for training at the plant control room simulator.

The key advantage of mimicking current control rooms comes from the ability to implement prototypes of new digital function displays into the existing analog control environment. Prior to full-scale deployment of technologies such as control room upgrades, it is essential to test the performance of the system and the human operators' use of the system in a realistic setting. In control room research simulators, upgraded systems can be integrated into a realistic representation of the actual system and validated against defined performance criteria. In this manner, control room upgrades are being designed, usability tested, and safety validated without the need to use the plant's training simulator.

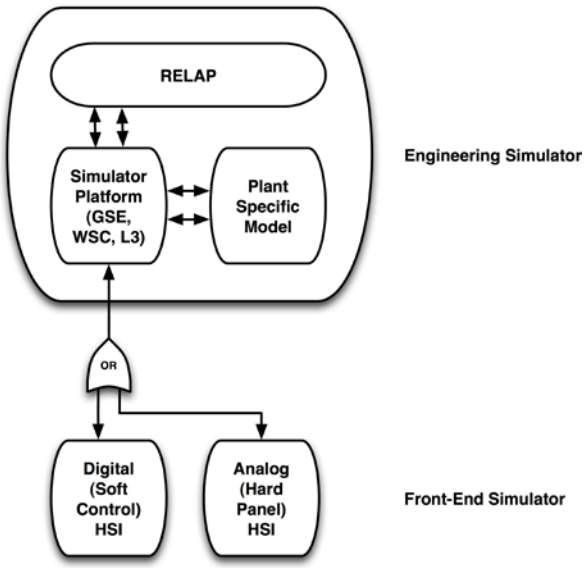

Figure 9. General Simulator Architecture

A full-scope plant simulator comprises several layers of systems as depicted in Figure 9. At the heart are system models that interact to create a realistic model of plant behavior, including thermal-hydraulic software modeling using RELAP, a vendor-specific simulator platform (e.g., simulator software development packages by GSE, WSC, and L-3), and a plant-specific model executed on the simulator platform. These models combine to form the back end called the engineering simulator. The engineering simulator interfaces with the front-end simulator, which consists of the control room HSI that the operator uses to understand plant states and control plant functions. The front-end simulator may take many forms such as an analog hard panel system found in typical U.S. training simulators or a digital soft control system found in some foreign plants and research simulators. Digital soft control systems may take the form of mimics to analog plant I&C or may represent advanced I&C that incorporates features such as overview displays and information rich trending displays.

In the first phase of the simulator buildout, represented by the current report, the INL has employed a workstation configuration consisting of four high-definition 30-inch displays at a resolution of 1920x1280 pixels (see Figure 10). These four displays correspond to any of the six main front panels depicted in Figure 5 and are likewise arranged in a horseshoe configuration around an operator desk. Each of these panels feature a number of windowed displays that can be pulled up from each display, corresponding to 114 detailed display screens. A series of composite snapshots of all subscreens per panel is depicted in Figures 11-16.

Figure 10. Current Workstation Based Full-Scope Simulator at INL

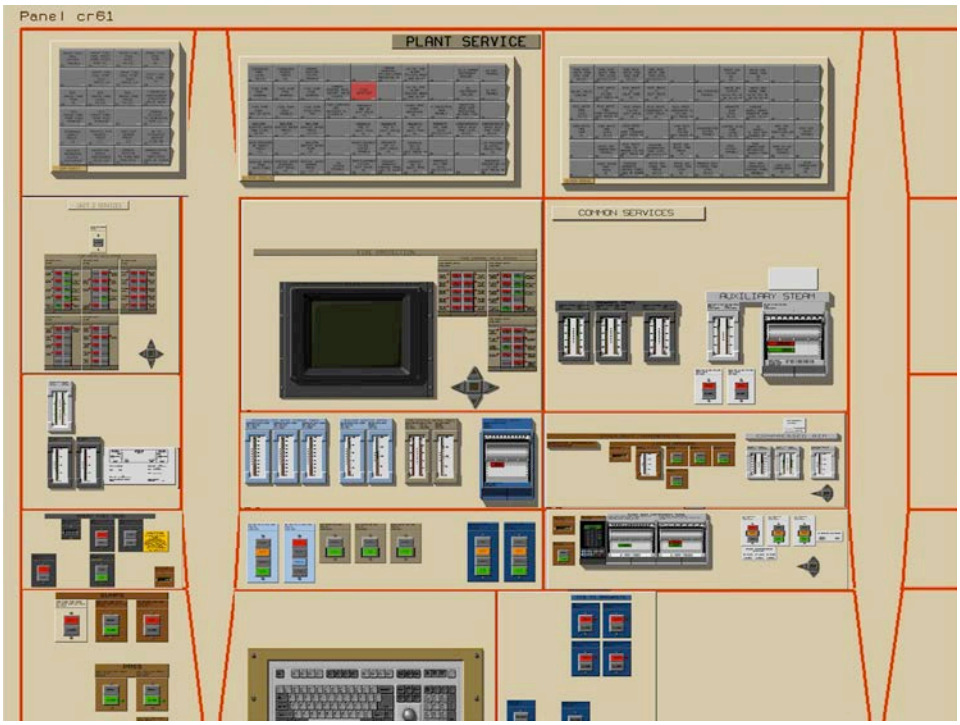

Figure 11. Composite Rendering of Simulator Windows for the Plant Services Panel

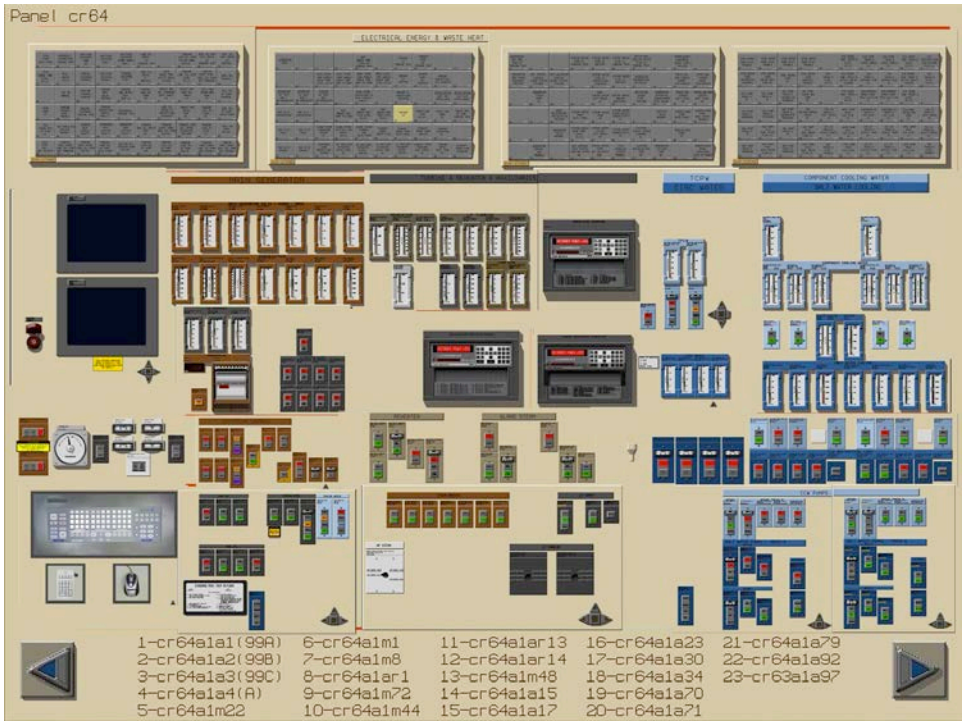

Figure 12. Composite Rendering of Simulator Windows for the Electrical Energy and Waste Heat Panel

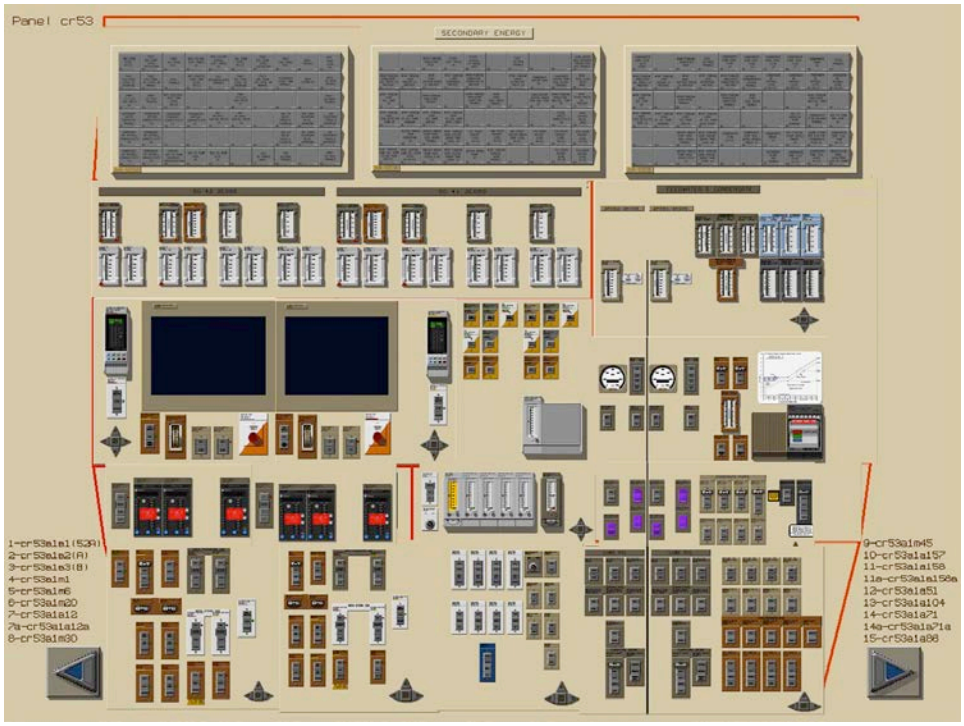

Figure 13. Composite Rendering of Simulator Windows for the Secondary Energy Panel

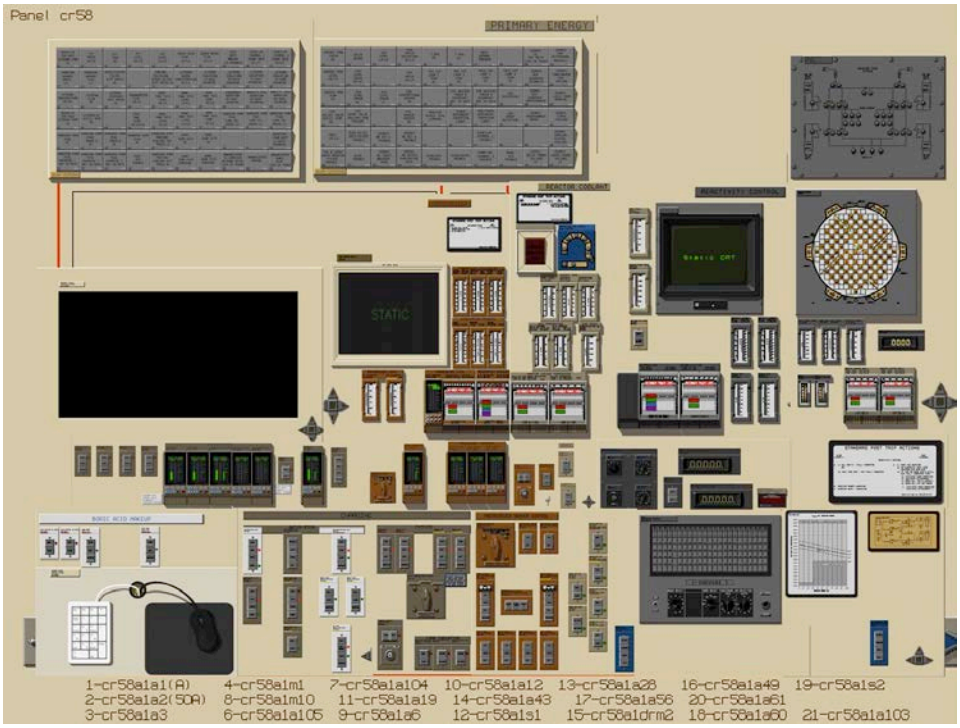

Figure 14. Composite Rendering of Simulator Windows for the Primary Energy Panel

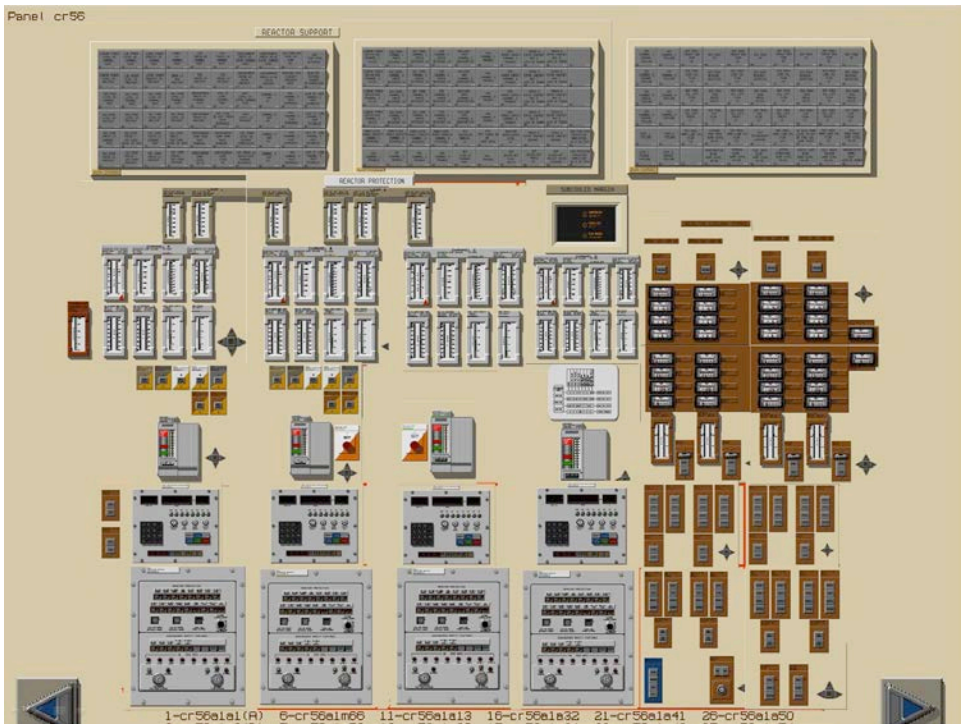

Figure 15. Composite Rendering of Simulator Windows for the Reactor Support Panel

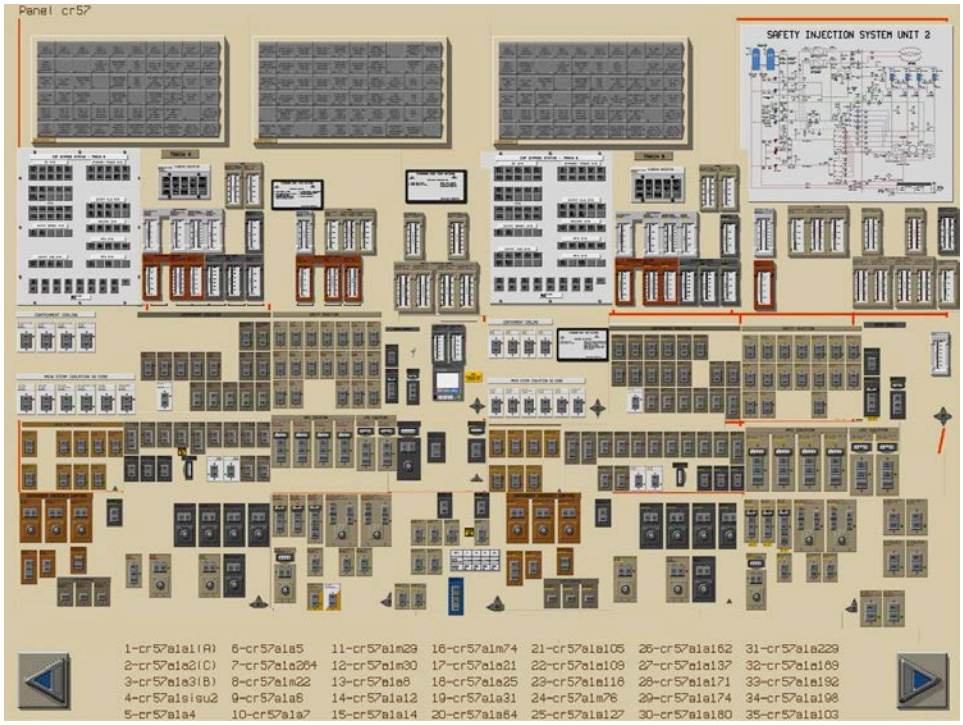

Figure 16. Composite Rendering of Simulator Windows for the Engineering Safety Features Panel

The hardware configuration consists of two high-performance Windows 98 based workstations, each equipped with a dual output video card capable of driving two displays. In the current configuration, one computer serves as the server, while the second serves as a client. The server and client are connected via a server switch, which allows the expansion of future clients operating under the server. A third workstation, currently being prepared by staff at SONGS, will host a runtime version of Westinghouse Ovation, which serves as the DCS that SONGS will be implementing for its control room upgrades. The Westinghouse Ovation DCS is not required for successful operation of the simulator model in its current form, since Ovation mimics are included in the L-3 Orchid simulator software. The Westinghouse Ovation DCS will be deployed at a later stage of buildout to support prototyping of digital replacement HSIs for the SONGS control room.

Beyond the basic installation of the SONGS control room simulator for use at INL, INL staff have participated in training at SONGS to familiarize themselves with the operation of the simulator and the types of scenarios employed in training. The startup script for the simulator is included in Appendix A to provide insights into the operation of the simulator in the current form. An explanation of an INL developed operator scenario is included in Appendix B.

To allow the simulator to display a variety of analog hard controls and allow the operator maximum interaction with the simulator, digital displays with touch interfaces are a viable and desirable solution. Popularly known as touchscreen displays, such displays can be set up in number of ways to mimic any control room configuration. The planned second phase of the simulator buildout will feature multiple L-3 Orchid Touch Interface bays. The primary difference between the current, Phase 1 buildout and the planned expansion is that the Orchid Touch Interface bays will provide a more realistic representation of the panels found in the current SONGS control room simulator. The configuration employed is comprised of three 46-inch LCD displays. The lower two displays feature touch screens to allow operators interaction with virtualized controls. The upper display, which is out of operator reach, is a non-augmented LCD screen without touch interaction. In a faithful mimic of a conventional control panel, the lower and upper panels are mounted at slight angles, with the lower display configured as a bench top area, while the upper display may be reserved for annunciators.

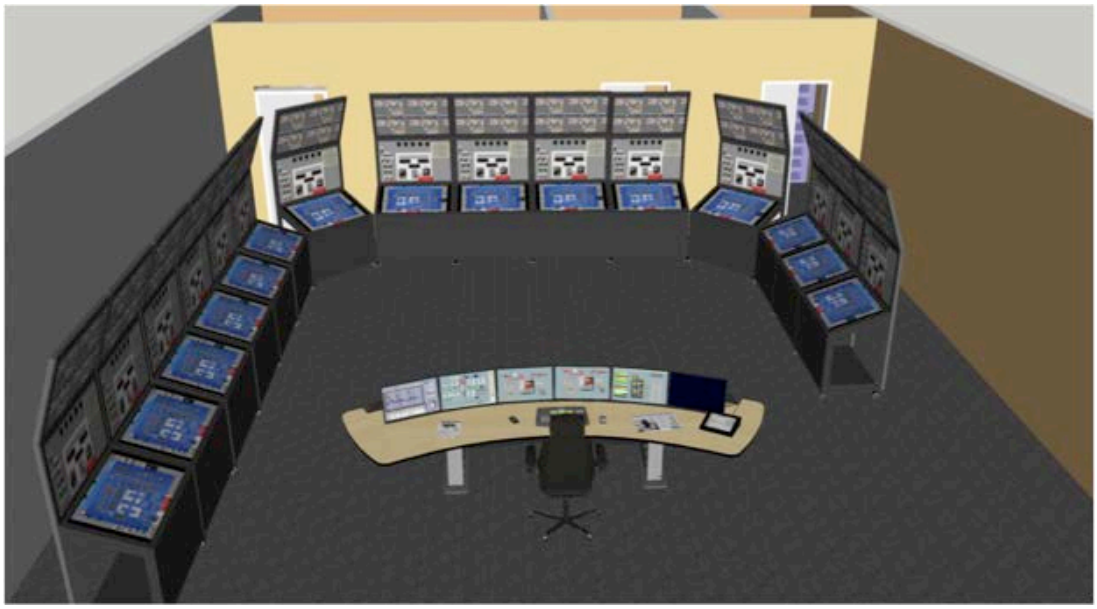

Figure 17. Proposed Control Room Layout Using Glass Top Panels

At the INL Human System Simulation Laboratory, the glass top panels will be linked together in a horseshoe shape that approximates the shape found in current control rooms. A depiction of 15 glass top bays in a linked fashion is found in Figure 17. Each glass top bay serves as a client to the central simulator server acquired through the first phase of the simulator buildout. Note, it is anticipated that the second phase of the buildout will encompass six bays, corresponding to a one-to-one relationship with the physical bays in the control room at SONGS. It is desirable in future phases to acquire additional bays to more realistically capture the scale of the physical simulator. Three bays chained together accurately represent the scale of each physical panel in the control room. Additional bays also allow greater resolution in the mimic of the analog I&C, creating a more realistic replication of the details of the actual control room and allowing greater detail in digital replacement components that will be introduced and tested in the simulator.

6. RESEARCH PATH FORWARD AND DISCUSSION

The control rooms at current nuclear reactors feature analog I&C technology in many cases dating back to the 1970s. Although this aging control room technology is adequately maintained to ensure reliability and safety, the cost to maintain such obsolete equipment is approaching or even exceeding the cost of replacement. Yet, there exist financial and regulatory hurdles to modernize control rooms, and vendors have been slow to provide comprehensive solutions that meet industry needs. The time required to perform a full-scale control room upgrade is significant, and the cost of loss of production for utilities reaches up to $2 million per day for a commercial reactor. Thus, wholesale modernization in the form of complete replacement of these control rooms is not likely in the U.S., and plants are adopting a piecemeal or system-by-system approach to upgrades.

As part of the LWRS Program, the INL is working with utility partners to develop a strategy for long-term control room modernization that will guide the development and deployment of new digital-based control room systems at existing U.S. nuclear power plants. The strategy will address how best to achieve an end state vision for the control room based on the plant concept of operations. This will include all aspects of operations such as procedures, degree of automation, and potential operator support systems. The INL is reviewing various control room modification strategies and management system principles and technologies for discussion with plant personnel to determine which strategies are most applicable to plants for incorporating digital controls and operator interface design into a traditional analog control room. Based on these discussions, the INL will propose an appropriate approach to establishing an end state vision for the plant control room and work with the utility partner to develop the vision.

While performing this task, INL personnel will conduct a needs analysis at a representative plant to determine concepts of operation and control room usage patterns and better establish an understanding of how operators use the current panels, displays, and controls and how they interact in a realistic setting. Initially, this will be done in the plant training simulator and will include documentation review, event reviews, procedure review, operator observations, and interviews with operations and maintenance staff, as well as engineering and modification team members and management. The needs will be prioritized in cooperation with the plant modification team.

The goals of this research include:

- Developing guidelines for standardizing operator interface screens based on human factors engineering principles
- Developing an end state vision for transitioning to a fully modernized MCR
- Developing, prototyping, and evaluating diverse I&C systems in a step-by-step fashion toward overall control room modernization
- Developing integrated digital I&C displays that combine the systems developed in step-by-step upgrades
- Providing first-of-a-kind proof-of-concept demonstrations of innovative HSI concepts

Integrated system validation (ISV) is a well-established concept in the nuclear industry [60]. Prior to full-scale deployment of technologies such as control room upgrades, it is essential to test the performance of the system and the human operators' use of the system in a realistic setting. Where simulator facilities are available such as in control room training simulators, upgraded systems can be integrated into a realistic representation of the actual system and validated against defined performance criteria. Less common, however, is the use of the training simulator as the development platform for novel interface elements.

In this report, we have briefly discussed the use of a full-scope training simulator for design and pretesting of proof-of-concept interface elements. The system in question is a copy of a nuclear power plant's active training simulator. Instead of buying commercial-off-the-shelf digital replacement systems or contracting custom systems that are developed offsite and only later integrated into the control room, the present approach uses the training simulator as the development platform and test bed. The approach affords considerable advantages over traditional ISV:

- The design process is formative, meaning it is possible to change ineffective elements of system design prior to full scale integration
- The design process is iterative, meaning it is possible to collect operator feedback at early stages of development and apply insights on operator performance into early-stage redesign
- The design process is environmentally driven, meaning it captures and mitigates constraints of the control room and aspects of the conduct of operations that might otherwise hinder successful implementation of an interface
- The design process converges on a standard, meaning the development of system-by-system upgrades affords the opportunity to create a style guide that may be used to drive a consistent design across the control room
- The design process is cost effective, meaning it is possible to take advantage of in-house engineering and human factors expertise to design and evaluate systems as they will actually be used.

In this report, we offer an example framework for using a training simulator as part of integrated system design in control room modernization projects. The simulator, when repurposed for research, provides the ideal platform for designing, prototyping, and validating new I&C concepts.

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Appendix A
Simulator Startup Procedure

Overview

This startup procedure provides a step-by-step guide, which should be followed at the initial startup of SONGS Simulator.

Note: this procedure does not include initial steps required to configure the simulator. Please refer to the Orchid IS Main Manual for information on initial setup of the simulator.

The startup procedures is broken down into the following scenarios:

1. Network Loader

This is to ensure that the simulator is loaded on the server. This step is performed only on the server.

2. Loading Orchid Instruction Station (Orchid IS)

This will load the default window of instruction station in a default mode.

3. Initialization of the simulator

This will allow the user to run the simulator as per the selected initial condition.

Network Loader

1. To access the network loader, double-click on the L-3 network loader icon, , on the desktop.
2. A *jNET* window, as in Figure 1, will appear.
3. Click on the icon, , in Figure 1 to load the simulator on server. Figure 2 will appear upon clicking the . The simulator server with initial configuration appears in a window.
4. Click the "Load" icon to load the server. Figure 3 will appear after clicking the "Load" icon.
5. A series of windows will open. **Do not close any window**.
6. If the simulator is loaded, all the tasks as shown in Figure 3, will appear green.
7. Minimize the network loader window.

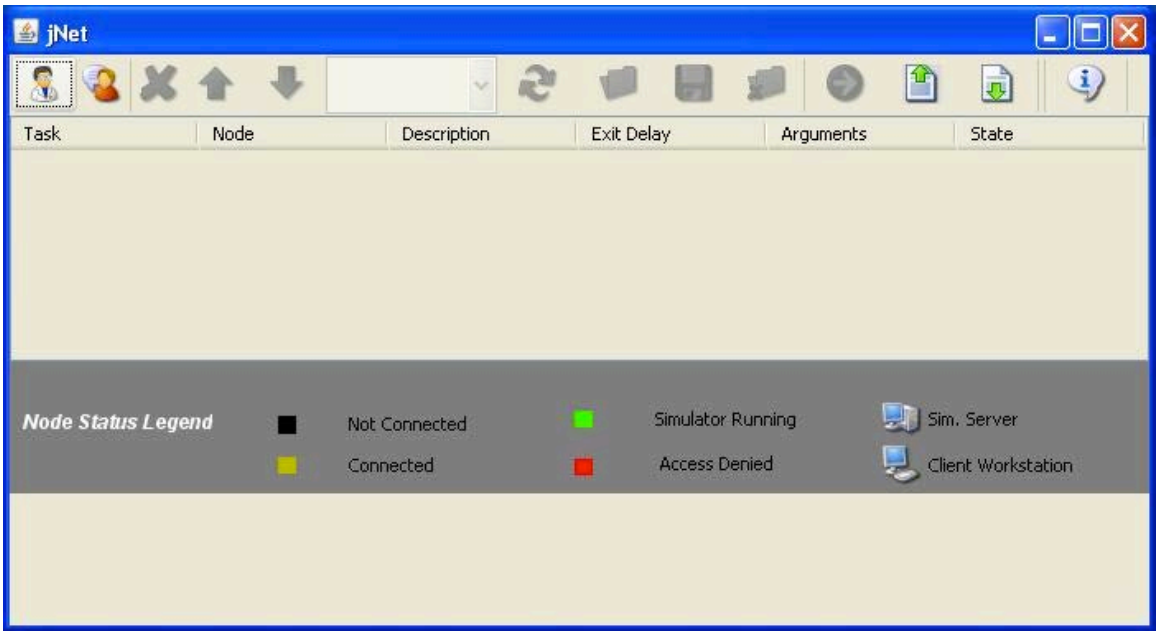

Figure 1. jNet Window.

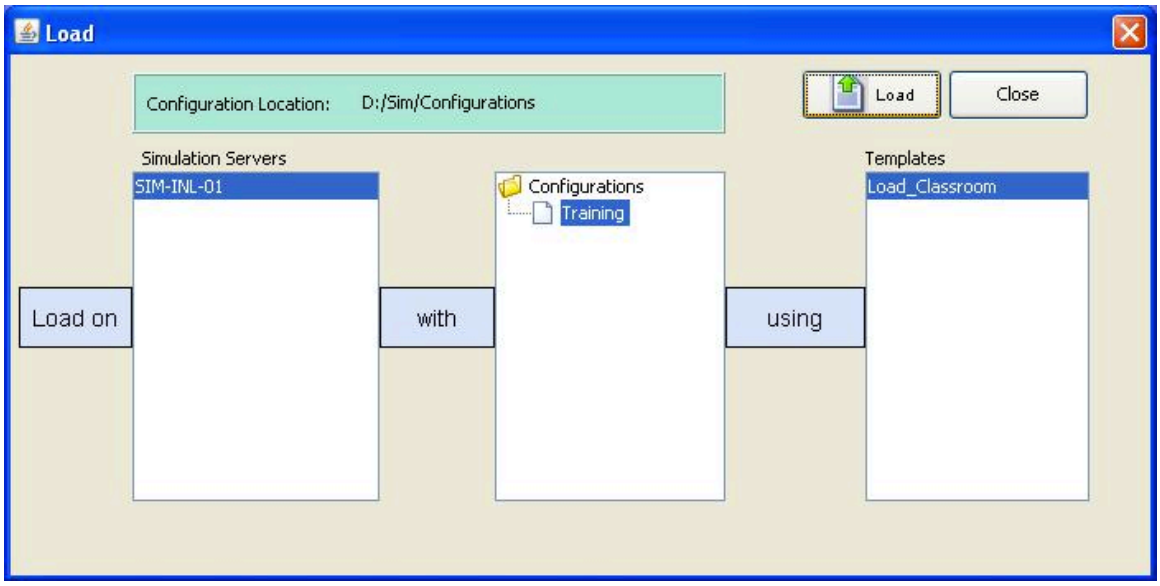

Figure 2. Upload the simulator. The highlighted simulator as in figure will appear on the screen.

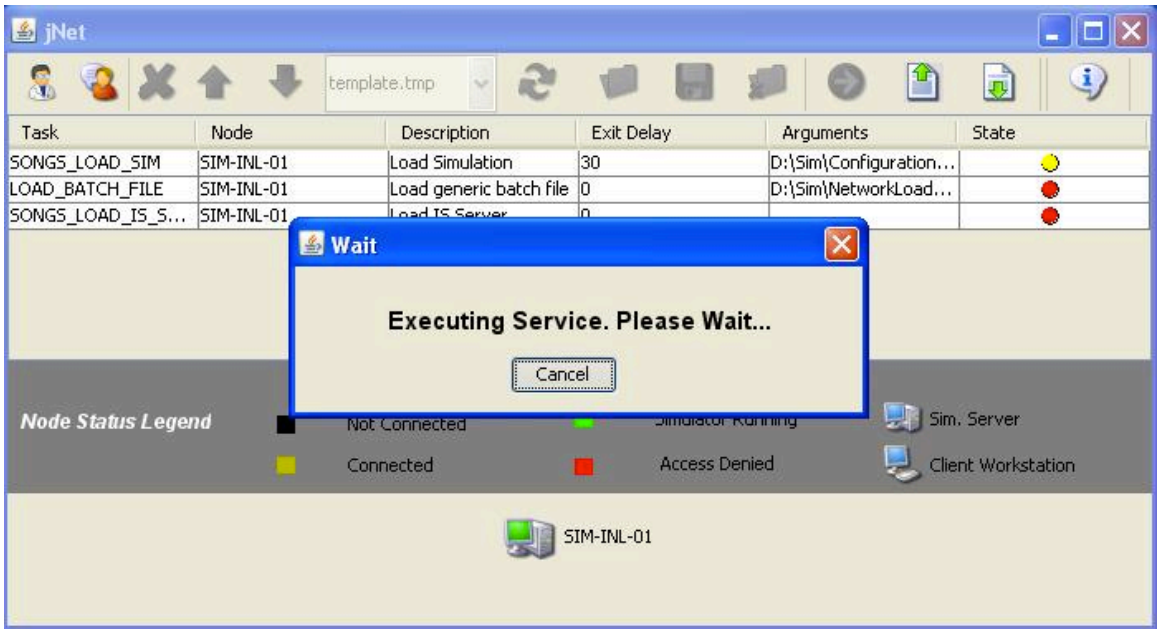

Figure 3. Loading the simulator on the server side.

On the Client side, simply double-click on the L3 network loader icon on the desktop.

Loading Orchid IS

1. To access Orchid IS, double-click on the Orchid IS icon, . The Orchid IS Server Load window will appear, as seen in Figure 4.
2. The default opening window, as seen in Figure 5, is displayed depending on the mode selected. Here the default mode is **Instructor**.
3. Figure 6 shows different areas of the main Orchid IS window. Also shows how to access the different controls and monitoring features.
4. On the **client side**, simply double-click on the Orchid IS icon.
5. The SONGS control room layout, as seen in Figure 7, is displayed by clicking on the "Panel" in the Menu Toolbar.
6. By clicking on each panel, control and display screens associated with that particular panel are displayed.
7. The control screens associated with each panel are ACTIVE only in the OPERATOR mode.
8. To change from the INSTRUCTOR mode (default) to the OPERATOR mode, click on "Mode" in the Main Bar. From the dropdown menu, select OPERATOR.

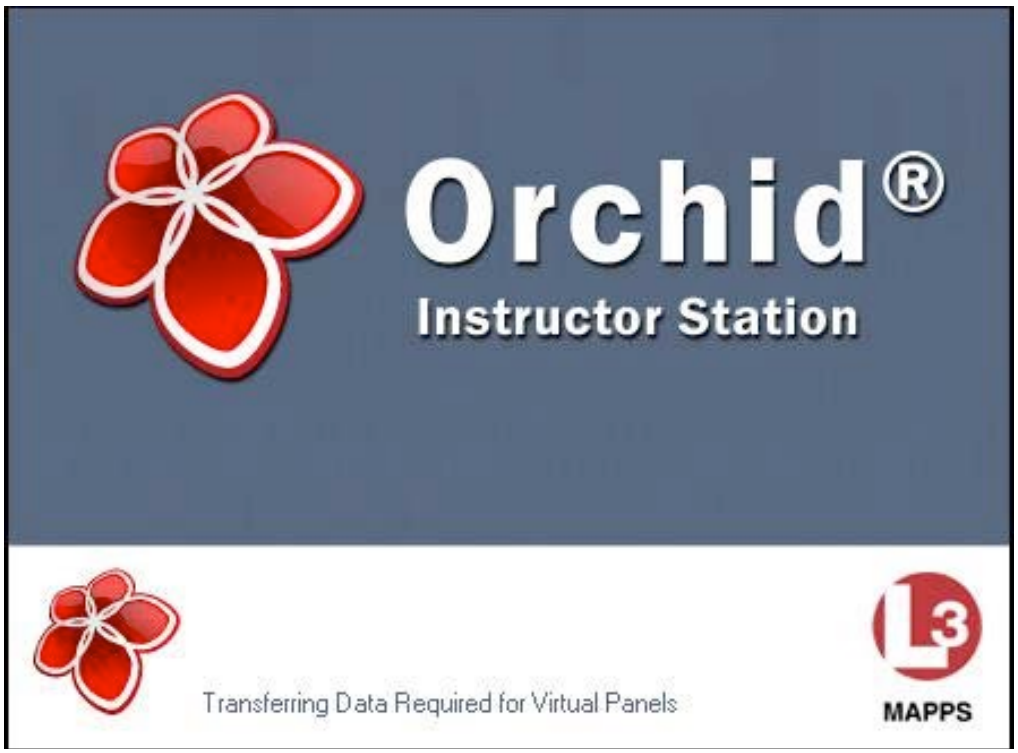

Figure 4. Orchid IS Loading Window.

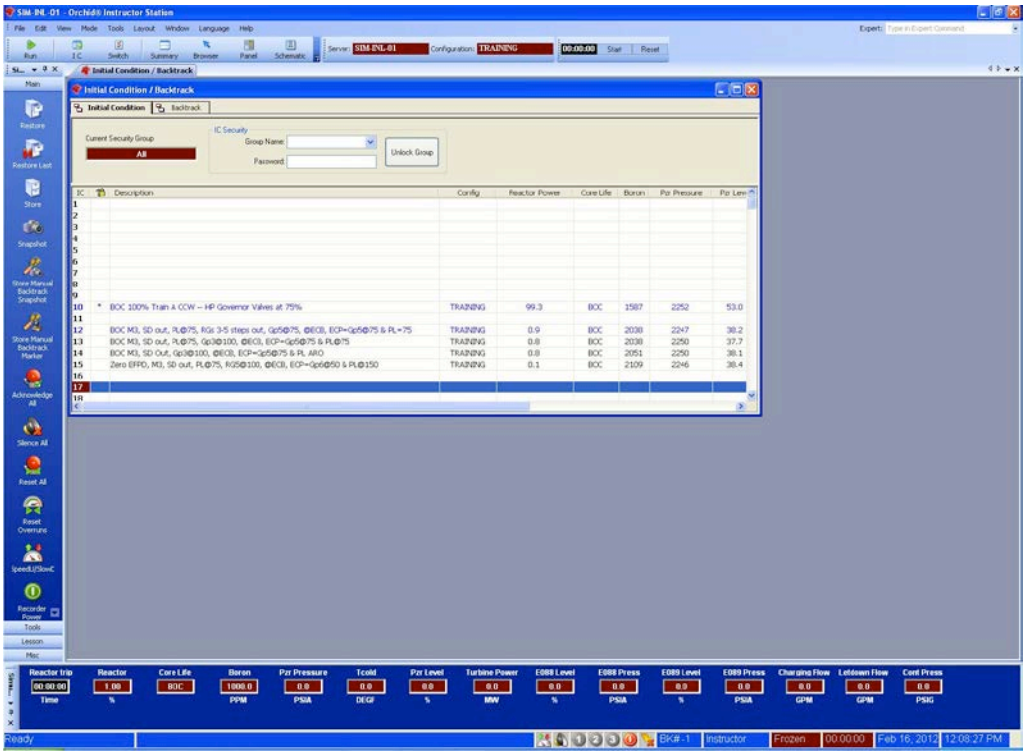

Figure 5. Default Orchid IS Window.

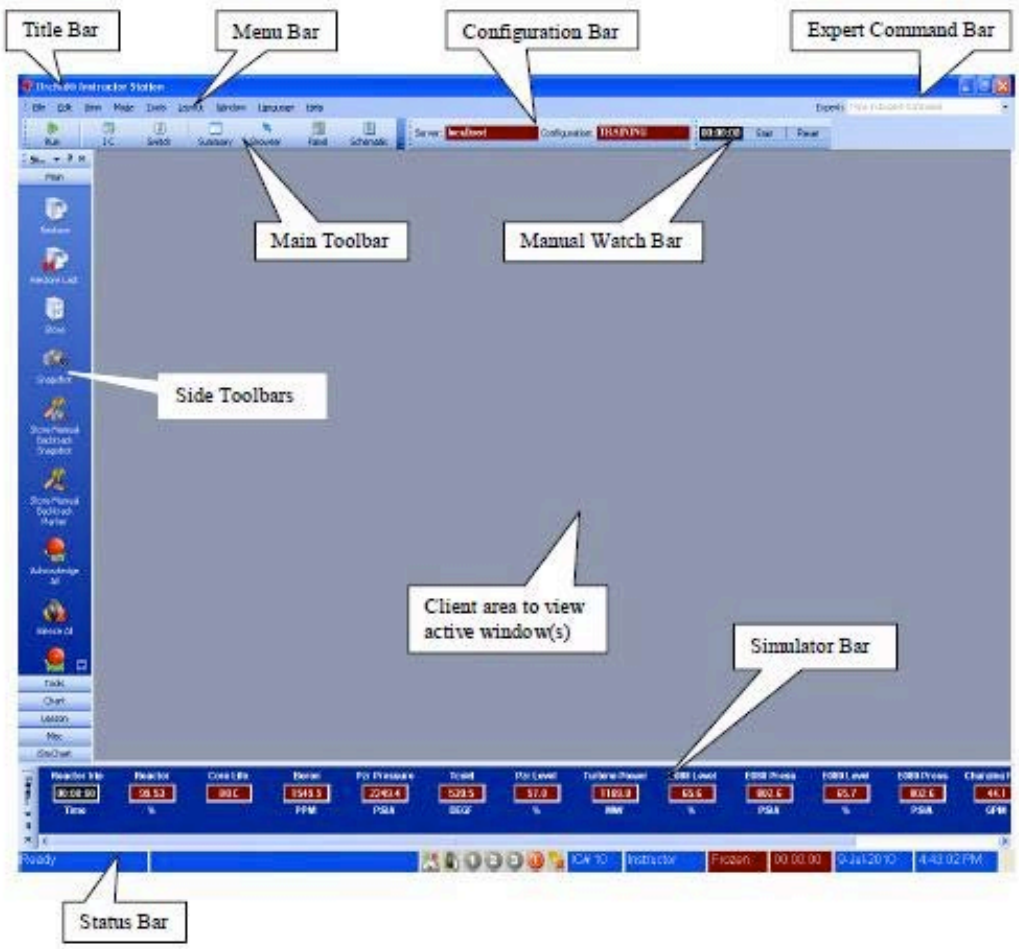

Figure 6. Different windows of the Orchid IS.

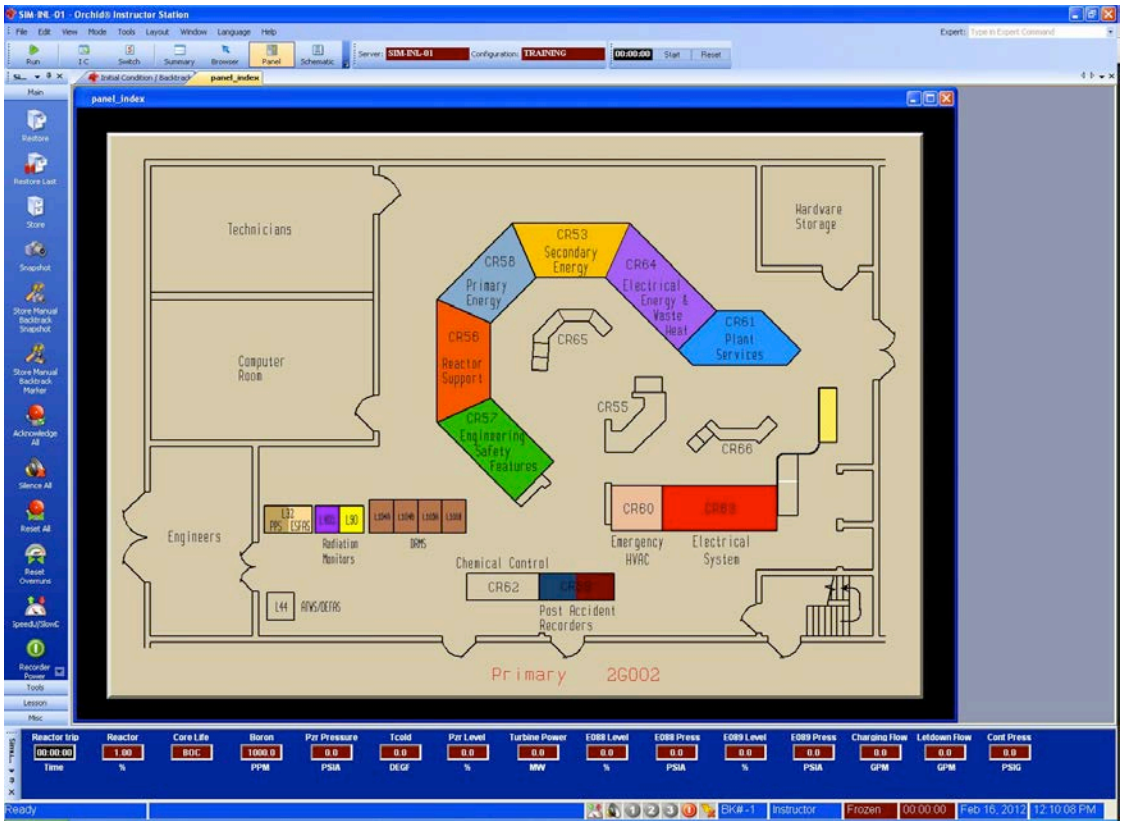

Figure 7. SONGS Panel Screen.

Note: For details on different areas of the main Orchid IS window, refer to the Orchid IS main manual.

Initialization of the Simulator

1. To run the simulator, select the RESTORE icon from the Side Toolbar under Main.
2. An Initial Condition-Restore window, as seen in Figure 8, will appear. Type 20 against the IC # and click OK. Here IC stands for Initial Condition.
3. Simulator both on the Server side and on the Client side will restore as per IC # 20.
4. Now to run the simulator as per the selected IC number, click on the RUN control in the Main Toolbar. The RUN control will change to FREEZE control. *Any action taken on the server is reflected on all the clients connected to the server*.
5. Observe that the values of different simulator parameter change in the Simulator Bar.
6. To stop the simulator, click on the FREEZE control.

Figure 8. IC assignment window.

Shutdown Procedure

1. Close the Orchid IS.
2. Restore the minimized network loader window. Click on the unload icon, . A window, as seen in Figure 9, will appear. Click on the "Unload" button.
3. All the open terminal windows will close.
4. Finally, close the network loader.

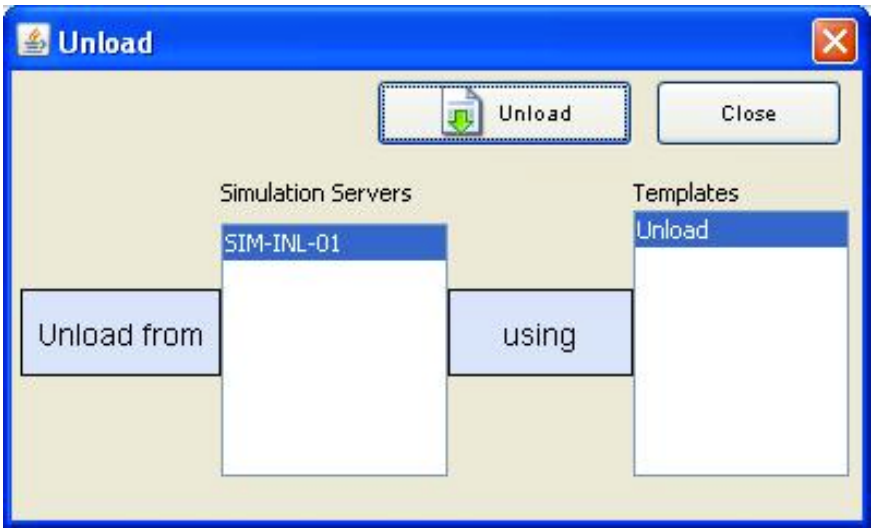

Figure 9. Simulator Unloading Window.

Appendix B
Creating a Scenario on the Simulator

Starting Scenario Manager

Accessing Scenario Manager
Prior to starting Scenario Manager, ensure that the simulator is loaded and Orchid IS Server is running on the server (see Appendix A). To launch Scenario Manager, click on Launch Scenario Manager button from Orchid® IS side toolbar under Tools tab. See Figure 1. The Scenario Manager Client window will appear as shown in Figure 2. Also labeled are different areas of Scenario Manager main window.

Figure 1. Launch Scenario Manager Button.

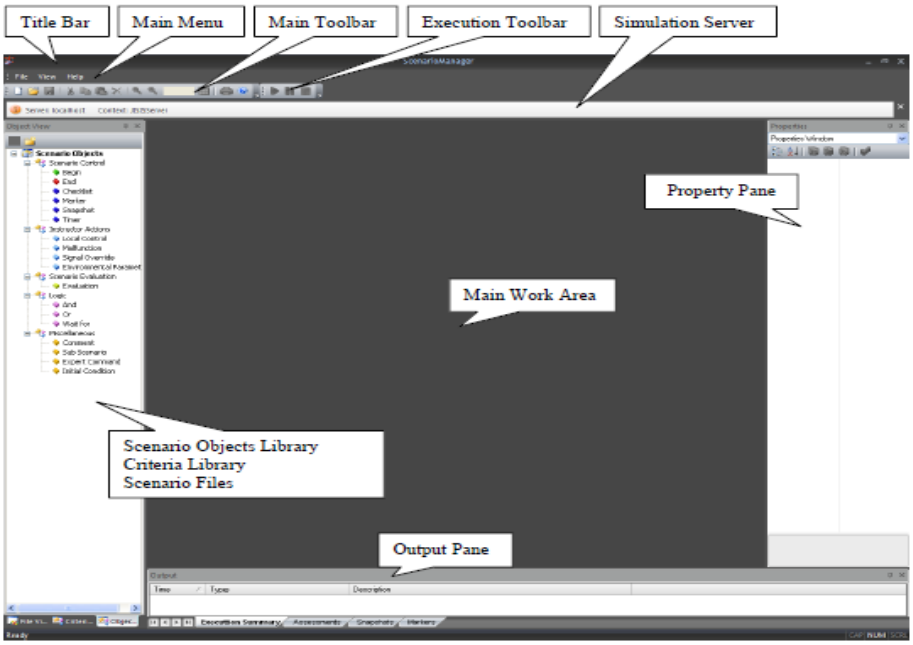

Figure 2. Scenario Manager Window.

The Scenario Objects Library is presented in an Object View Pane as depicted in Figure 3. It shows all the available scenario objects that can be used in a scenario. The scenario objects are classified into libraries based on object functionality. For details about each library, see L-3/MAPPS (2005).

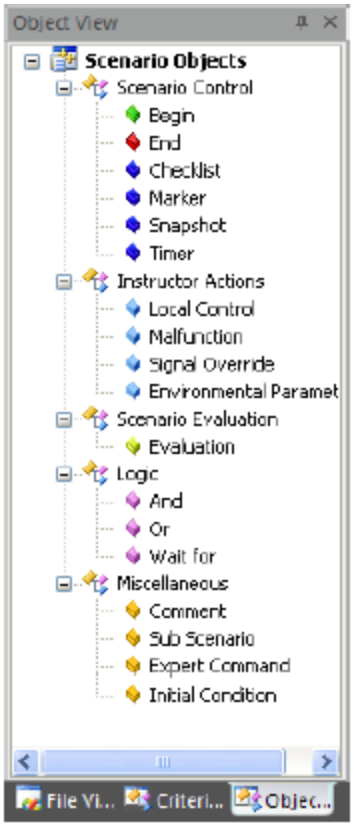

Figure 3. Object View Pane.

Using Scenario Manager

The Scenario Manager can be used for editing scenarios and managing scenario files and folders. It can also be used for executing scenarios. A loss of coolant accident (LOCA) scenario has been created using the Scenario Object Library for demonstration. The steps involved in the design of the LOCA scenario using the Orchid Instruction Station, resulting in a reactor trip as explained below. In executing this scenario, there would typically be an instructor who controls the simulator and an operator who controls the simulated plant.

Creating a Scenario

1. To create a new scenario, select New from the Main Menu's File option or click on the new button from the Main Toolbar. This operation will open a blank scenario in the work area as in Figure 4.
2. A scenario is composed of scenario objects connected together in a structured manner. A scenario flow diagram must contain a *Begin object*, which identifies the entry point for the scenario execution. The scenario flow diagram must always end with the *End object*, which identifies the end point for the scenario execution. The entire LOCA scenario flow diagram is presented in Figure 5.

3. Following the Begin object, *Initial Condition Object*, is selected and the initial condition (IC) to which simulator is to be restored is entered under object properties that appear in the property pane. In the present scenario, IC number 20 is selected.
4. The *Expert Command Object*, is selected that executes the simulator.
5. The *Checklist Object* from scenario control is selected to execute the LOCA scenario. Under Checklist Object properties, manual option is selected. This allows the instructor to manually initiate the LOCA scenario.
6. The *Malfunction Object* from the Instruction Actions is selected. Under Object properties, the component label at which LOCA is to be initiated along with associated parameter values can be set.
7. Again Checklist Object is selected in manual mode to confirm that LOCA scenario is executed and the reactor has tripped automatically. If there is an error in the execution of the LOCA scenario and the reactor does not trip, then the instructor has the option to check the box NO, indicating that an error occurred. Otherwise, the instructor can check the box Yes, indicating the LOCA scenario occurred and the reactor tripped.
8. As mentioned earlier, the last Object in the scenario flow diagram is END. The END object freezes the simulator.

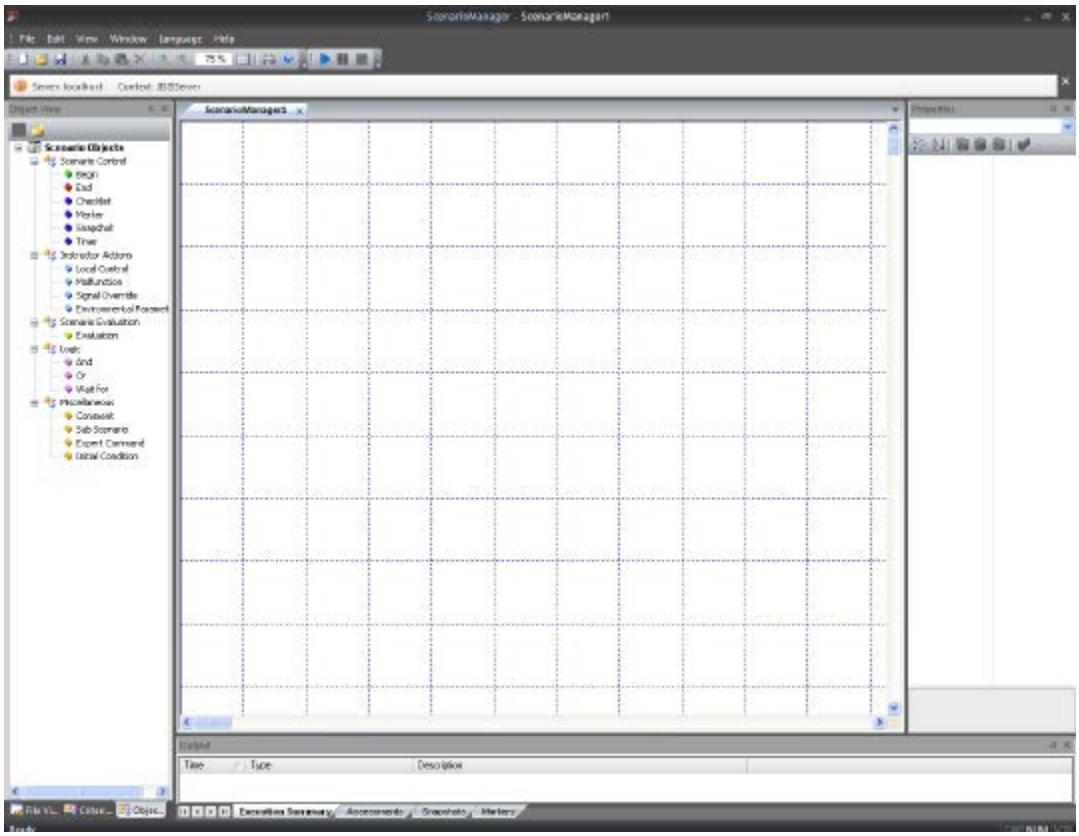

Figure 4. New Scenario blank window.

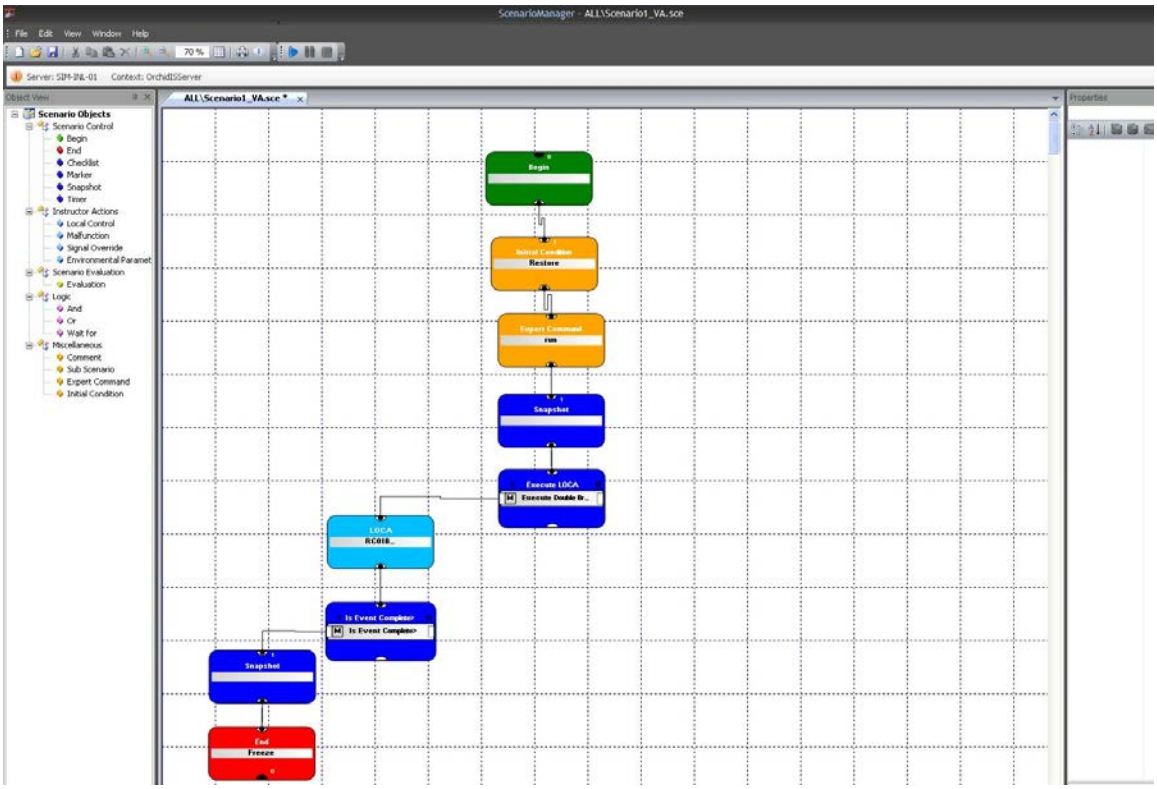

Figure 5. The Loss of Coolant Accident (LOCA) Scenario.

Starting (Executing) Scenario

To execute a scenario, click on the Execute button from the execution toolbar. When a scenario starts executing, its corresponding tab on the main work area changes to red color and the scenario file's icon displayed in the File View pane changes also to the scenario executing icon, as seen in Figure 6.

As the scenario execution progresses, the scenario objects are dynamically updated, and they can be in one of the following states that is highlighted by different object execution state colors.

Red – Successful execution state
Orange – In execution state
Magenta – Error execution state
Blue – Restored execution state
Gray – Bypassed execution state

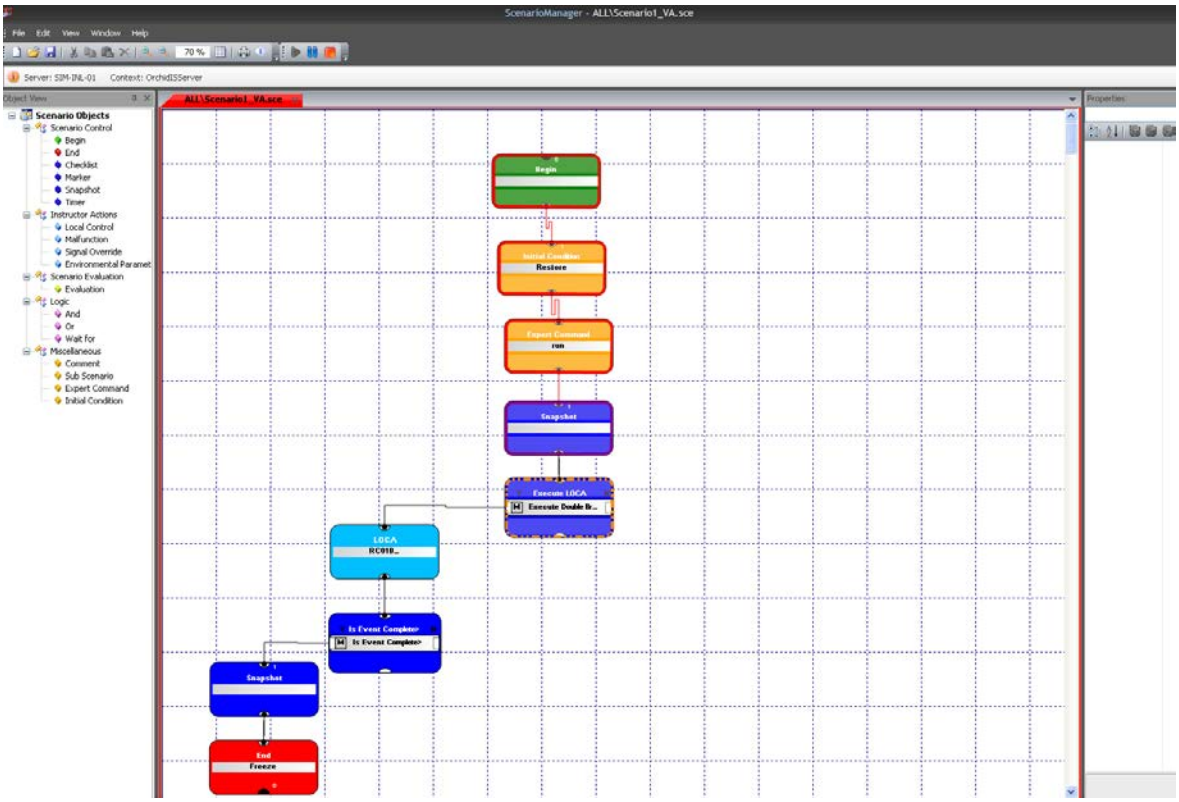

Figure 6. Execution of the LOCA scenario.

Using a similar procedure to the one described above and other Objects from the scenario object library, many different malfunction scenarios can be created.

Reference

L-3/MAPPS. (2005). *Orchid Instruction Station: Scenario Manager User Manual Version 5.12.0 Revision B*. Montreal: L-3/MAPPS.