INL/CON-12-25120
PREPRINT

The Development of a Human Systems Simulation Laboratory: Strategic Direction

American Nuclear Society (NPIC&HMIT)

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July 2012

THE DEVELOPMENT OF A HUMAN SYSTEMS SIMULATION LABORATORY: STRATEGIC DIRECTION

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ABSTRACT

The Human System Simulation Laboratory (HSSL) at the Idaho National Laboratory is one of few facilities of its kind that allows human factors researchers to evaluate various aspects of human performance and human system interaction for proposed reactor designs and upgrades. A basic system architecture, physical configuration and simulation capability were established to enable human factors researchers to support multiple, simultaneous simulations and also different power plant technologies. Although still evolving in terms of its technical and functional architecture, the HSSL is already proving its worth in supporting current and future nuclear industry needs for light water reactor sustainability and small modular reactors. The evolution of the HSSL is focused on continual physical and functional refinement to make it a fully equipped, reconfigurable facility where advanced research, testing and validation studies can be conducted on a wider range of reactor technologies. This requires the implementation of additional plant models to produce empirical research data on human performance with emerging human-system interaction technologies. Additional beneficiaries of this information include system designers and HRA practitioners. To ensure that results of control room crew studies will be generalizable to the existing and evolving fleet of US reactors, future expansion of the HSSL may also include other SMR plant models, plant-specific simulators and a generic plant model aligned to the current generation of pressurized water reactors (PWRs) and future advanced reactor designs. Collaboration with industry partners is also proving to be a vital component of the facility as this helps to establish a formal basis for current and future human performance experiments to support nuclear industry objectives. A long-range Program Plan has been developed for the HSSL to ensure that the facility will support not only the Department of Energy's Light Water Reactor Sustainability Program, but also to provide human factors guidance for all future developments of the nuclear industry.

Key Words: human systems simulation, human factors, strategy, program plan

1 INTRODUCTION

The United States is experiencing a rapid growth in energy needs and in response to this the nuclear industry has identified a number of urgent research needs from current industry trends and developments. These needs are specifically in the areas of long-term sustainability of the existing reactor fleet and the associated reactor technology, materials, and instrumentation and control (I&C) technology. In support of industry needs, the US Department of Energy is sponsoring research, development, and deployment of advanced technologies and operating concepts for several programs, including Light Water Reactor Sustainability (LWRS), Nuclear Energy Enabling Technologies (NEET), and Small Modular Reactors (SMR). These programs include the requirement to investigate human reliability, safety, human performance, and human factors engineering (HFE) methods and tools.

One of the "hot issues" in the nuclear industry is control room modernization; current control rooms in the US are based on dated analog technologies and it is difficult and costly for utilities to maintain them. To support the transition from outdated technologies and associated operating concepts, it has become a pressing need to establish a research facility that can have a positive impact on the industry's hot issues. As part of the LWRS program, and in response to the growing need in the industry for human factors guidance in NPP upgrades and new designs, the Idaho National Laboratory (INL) is working closely with nuclear utilities to evaluate and develop technologies and solutions to help ensure the safe operational life extension of current nuclear power plants (NPPs). One of the most significant developments at the INL is the reconfigurable control room simulator (officially known as the Human System Simulation Laboratory, or HSSL) that is used to develop and test the implementation of newer, digital control room systems and associated operating concepts (Boring, 2009).

2 INDUSTRY NEEDS

The use of simulators in industry is not new. Plant and process simulators are widely accepted as a valid, reliable and cost-effective means to evaluate and validate a large range of issues in many industries, from technology decisions, to operating concepts, to human performance. Unfortunately few facilities like this are available to the US nuclear industry. Rather, each utility has its own simulator that mimics its current control room. While all US utilities use these simulators for training and licensing of operators, they are not generally available for research purposes or for evaluation of new technology.

The INL has recognized this need several years ago and has established the HSSL to start addressing the gap. The first version of the HSSL was launched in 2007 and it had slowly evolved until the current version was installed in 2009 in a space shared with the Center for Advanced Modeling and Simulation. From the beginning the focus had been on task measurements, performance shaping factors, human reliability, visualization and usability. Collaborators included NASA AMES, DoD and the NRC. The first exploration of NPP simulations involved collaboration with a US utility that had made its plant simulator available for research on visualization and human performance. Much of this early work lacked a formal framework, partly due to the immaturity of the facility, the lack of research staff, and the lack of a formal statement of requirement from stakeholders.

A report by Le Blanc et al. (2010) described the HSSL's infrastructure and capabilities and the methods that had been applied to measure human performance in the facility. The lab has seen some significant changes since then and stakeholders in the nuclear industry are currently aware of INL's intention to develop more capacity. However, stakeholders have until recently not been directly involved in the lab's activity, nor its plans for expansion. This is now changing and the INL is taking a more strategic stance as part of its role in the LWRS program. This strategic role includes addressing long-standing problems like the scientific evaluation of human performance with advanced HSI technologies, control room staffing, operator workload, the need for operator situational awareness, upgrades of alarm systems, new concepts of operation for new reactor types, and many more.

3 RESEARCH DIRECTION AND RESOURCES

The HSSL supports various LWRS initiatives, including control room modernization, digital upgrades, alarm management, computerized procedures, advanced human-system interfaces, advanced operating concepts, and advanced outage management concepts. The INL's expertise in human factors is applied to the evaluation of these technologies in operator-in-the-loop experiments in the HSSL. This includes the study of the effect of advanced HSI concepts on human performance, as part of the NEET and SMR programs.

Because the HSSL is a plant- and technology-independent environment for full-scope as well as part-task testing of operator performance in various control room configurations, it serves as a neutral testbed for implementing new control room technologies, especially digital I&C systems and human-system interfaces. Although plant-specific simulations are available, the HSSL is not limited to a particular plant or simulator architecture. In fact, through collaboration with the University of Idaho, simulations have also been established for control of chemical processes and for transportation. Design principles from such smaller simulations may be extracted to support developments in the nuclear field and used to establish first principles for advanced display design. In addition, with the University of Central Florida's collaboration, mixed test bed software that allows for advanced data logging and measurement during human-in-the-loop testing will strengthen existing data collection and analysis methods. The facility currently employs various software and hardware platforms to run a plant-specific LWR simulation, a number of small generic simulations, and one SMR simulation. With improved reconfigurability currently being developed, it is possible to change the operator's interface to digital panels and also to different control modalities, such as those employing higher levels of plant automation, advanced operator interfaces and advanced alarm filtering.

The simulator also serves as a resource for testing the application of emerging technologies in NPP control rooms. Because emerging I&C technologies can face significant regulatory lead times, conducting early testing of operator performance with advanced technologies can help to ensure the safety and usability of systems prior to large-scale deployment and costly verification and validation at the plant. Early testing using the operator performance metrics developed in the HSSL can help ensure that upgrades meet regulatory requirements.

While it is not the purpose of the HSSL to validate operator training and certification programs, its ability to provide reliable predictions of operator performance and control room behavior would in future make it a valuable resource to trainers. Results obtained from part-task scenarios would help trainers understand what aspects of human performance to measure in a simulator that would predict real-world control room behavior. An important aspect of the use of the HSSL to support trainers is its physical and organizational separation from the power plant. This enables INL researchers and utility trainers to bring operators into the HSSL and allow them to evaluate operating concepts and technologies without the mental and organizational inhibitions that would otherwise make it difficult from them to open up and make mistakes in order to learn something new.

To meet all of these challenges, the focus of the HSSL activities is twofold: 1) to support the DOE's initiatives to help the nuclear industry meet the objectives of producing safe and sustainable energy by testing different technologies prior to deploying their upgrade, and 2) to develop new concepts based on human factors principles that will establish the technical basis for the selection and implementation of new human-centered technologies at nuclear power plants.

Through interaction with various agencies and industry collaborators, a number of broad and specific research needs have been identified and these needs are providing a clear indication of the direction that the INL will take with the HSSL in future. From interaction with many representatives from industry over the past year, a number of requirements and expectations have been identified, leading to the definition of five focus areas (Figure 1):

Figure 1: Research Topics

1. Evolving Concepts of Operation and the role of the Operator in Nuclear Power Plants

Increased automation not only affects the role of the operator in the control room, but cuts across many aspects of plant operations and maintenance from process control, to decision support, to HSI management, to routine tasks such as keeping logs. The HSSL will identify effective tools to develop and evaluate alternative concepts of operation to determine when to encourage shared control between humans and automation and when to assign final authority to the humans by studying of operator roles that separate the monitoring of plant status and supervision of automation. Results from this research topic include ergonomic guidelines for fully digital or hybrid NPP control rooms, especially for interactions between occupants, human-system interfaces, workstations, and control boards.

2. Human System Interface Design Principles for Supporting Operator Cognitive Functions

The HSSL will focus a large part of its work on developing a better understanding of what creates cognitive burden in NPP operations and how best to apply advance human-system interface technologies to improve proceduralized tasks, communications, and teamwork. One of the important requirements for implementation of new technologies is to develop detailed guidance and acceptance criteria for addressing integrated system validation (ISV).

3. Information Presentation to Address Emergent Complexity in Advanced Systems

Research is necessary to develop tools to measure procedural, cognitive and visual complexity in the control room so that a better understanding of the effects of different types of information presentation can be achieved. Although NPP designers are seeking greater simplicity, the end result of reduced transparency and more tightly coupled dependence among systems sharing the same information highway may serve to increase complexity in relatively new ways. For example, crews may prioritize actions differently, or because information is localized per workstation operators fail to maintain the same mental model regarding plant status. The HSSL will investigate to what extent increases in sensing capabilities, information processing support, intelligent agents, automation, and software-mediated interfaces affect human performance due to the increase in abstraction and the "distance" between personnel and the physical plant, the nature and extent of dependencies, and emergent cognitive complexity associated with understanding these relationships.

4. Human-system interaction for Safety Significant Actions

This topic deals with the relationship between the demands placed on the operator by the performance characteristics of the plant, such as timing and accuracy requirements, the support provided to the operator by the human-system interface, and the reliability with which the operator can perform the required functions, all within the context of the plant safety basis. Particular attention is paid to the effectiveness, efficiency, safety and reliability with which an operator can perform specific tasks in a specific operational context (normal or emergency). This includes the effect on human performance with different technologies and different HSI configurations.

5. Human Factors Engineering Methods and Tools

A significant part of the HSSL's capacity will be devoted to evaluation and development of advanced human factors metrics, methods and tools associated with advanced digital information and control systems. This will help to validate human performance models for the nuclear industry and determine which criteria are necessary for validation and regulatory acceptance and integration into a risk assessment framework.

4 STRATEGIC OBJECTIVES AND ACTION PLANS

The HSSL Program Plan describes the INL's strategic mission, vision, functions and research objectives for the facility. These have been defined with the specific purpose of ensuring that the HSSL would be relevant and responsive to industry needs. In particular, the Program Plan states that the strategic goal of the HSSL is "*to implement and maintain a world-class simulator-based facility to perform basic and applied research that supports the nuclear industry's need to incorporate human factors principles in the design, construction, operation and maintenance of nuclear facilities*". Achievement of this goal will help to develop the HSSL into the leading facility in the US for validation of new operational concepts and technologies, thereby ensuring that nuclear plant modernization of I&C systems and control rooms is based on demonstrated and validated scientific principles and data.

The HSSL short-term action plan includes three main programmatic activities required to implement the focus areas described earlier:

1. Implement NPP simulator models that are representative of the most important technologies being employed in the US: pressurized water reactor (PWR) and boiling water reactor (BWR) systems, and also a new generation of small modular reactors (SMRs);
2. Conduct experiments in advanced I&C systems, human factors and power plant operations in controlled settings representative of generic as well as specific nuclear industry conditions and requirements;
3. Identify, develop and test tools, methods and performance measures necessary for human factors research within this environment. This includes up-to-date techniques for function allocation, task analysis, computational human performance modeling, human reliability analysis, and human-system interface design.

The action plan also requires increasing collaboration with nuclear industry organizations, universities and other approved agencies to build and retain the skills needed to improve nuclear technology and nuclear plant safety. The unique strengths of the HSSL that will be leveraged are considered to be the INL's relationship with the utilities and its long-standing regulatory perspective with regard to human performance, safety and licensability of designs.

5 EVOLUTION OF THE HSSL

In addition to the external requirements for a simulator-based research facility described above, some of the recent plans to upgrade the HSSL were generated from internal project requirements. Most of the INL's human factors projects are multidisciplinary and interdependent and require a dedicated, shared laboratory space that meets standards and requirements for studies with human participants in general and studies of human interaction with technology in particular. The requirements shared by multidisciplinary projects (that is, projects that have human factors, I&C and operational elements) include dedicated, independent, but linked laboratory spaces with the necessary supporting infrastructure. Projects have overlapping, common and individual physical as well as functional boundaries. It has been our experience that, in addition to human factors expertise, modeling, simulation and experimental facilities, almost all projects also require nuclear operations, I&C, and software expertise. In fact, a full time dedicated simulation engineer has been found to be a requisite staffing component.

Another important requirement of the HSSL is a dedicated experimenters' gallery to allow for observation, audio-video recording, and recording of physiological response of crews. Some of these requirements will be satisfied by current enhancements of the HSSL facilities. Others, especially those involving significant structural and equipment upgrades will form part of the HSSL's long term plan.

The HSSL program represents a long term commitment spanning 10+ years. In its current configuration, the HSSL provides the high-fidelity simulation and visualization capabilities needed for projects involving the development and evaluation of new technologies for control centers. Several pilot projects are currently underway that involve the evaluation of HSI technologies, operating concepts or advanced control room visualizations. For this purpose new technologies are first staged in the HSSL for proof-of-concept testing prior to demonstration and evaluation at host nuclear power plants or other approved installations. The HSSL facilities are configured in a variety of settings according to the functional context of each type of plant's control center.

To meet the needs of each type of user, the HSSL will require new capabilities and upgrades as research projects progress. Over time, this will result in a facility with highly complex, flexible, and sophisticated features that will enable realistic modeling of the changing tasks and functions required of the various plant control centers.

In order to meet the needs of diverse multi-disciplinary projects, the HSSL Program Plan outlines an evolution plan for HSSL facilities and configuration over a ten-year period. The following major phases are envisaged:

- **Year 1 (current):** The HSSL (which is currently still accommodated in the Center for Advanced Energy Studies) is being equipped with additional hardware (touch screen panels and servers) and simulation software to support pilot projects in general, and specifically digital upgrades for analog control rooms. This includes the installation of a full plant simulator and associated hardware and software. Additional process simulation software from the University of Idaho and a Small Modular Reactor simulator are also available for experiments. Collaborative R&D agreements are in place with a number of universities, utilities and vendors to support research projects, such as the development of HSI prototypes to test advanced display concepts for specific scenarios.
- **Year 2:** The HSSL will be relocated to a dedicated space in another building in the INL complex. The new HSSL layout will specifically be designed for maximum reconfigurability, including dual operator stations to simulate a two-unit control room. This will enable research on function allocation, staffing, situation awareness and workload in multiple-unit control rooms. The upgraded facility will coincide with research into human performance issues involved with degraded I&C during and following external events and emergent issues.
- **Year 3 - 5:** Further enhancements to hardware and software will significantly improve the INL's ability to perform in-depth simulator studies and it is envisaged that part of the HSSL capacity may

be dedicated to conducting research in support of utility upgrades, modifications and new designs. Specific attention will be paid to human factors issues in the transition from analog to digital controls and displays and the integration of field worker processes with the main control room, including simulation of operator interaction with an advanced outage control center. During this period intensive research in computerized procedures and task-based HSIs will be conducted, leading to the development of updated guidance on human performance with advanced operator support features.

- **Year 6 – 10**: A further major upgrade is planned for this period to allow investigations into future concepts of operations. This will include upgrades of all plant simulations and installation of additional plant models to match the current state of advanced power plant control and automation schemes in the industry. Technology upgrades are expected to include simulation of centralized on-line plant monitoring facilities, advanced decision support software, and hardware upgrades to support the implementation of advanced emergency response facilities in support of investigation of emergent issues during conditions of degraded I&C. It is expected that research during this phase will be focused on human performance implications of increased complexity in the control room due to an increase in the amount of information flowing into the control room, accompanied by a change in the role of the operator due to changing automation schemes and concepts of operation.

6 WORK IN PROGRESS

Through the DOE LWRS program, the INL is leveraging design concepts obtained from the HSSL to evaluate the use of hand held mobile devices and software to support various aspects of field work for the LWRS program as well as the INL's Advanced Test Reactor. In both instances, HSSL staff and supporting hardware and software are used to rapidly prototype display interfaces on various handheld devices. The INL is collaborating with vendors in developing communications software and different communication protocols for rapid updating and feedback between the control room and workers in the plant.

Design approaches originated in the HSSL and in collaboration with industry partners will be migrated to the users through a graded approach. This will include proof of concept testing to be followed by more rigorous examination. At the same time, we are embarking on research that evaluates the human factors engineering processes and criteria for system-by-system upgrade from analog to digital for utilities. Both of these efforts support the DOE LWRS program and are organized from within the HSSL. Results will be produced during the latter half of 2012. Many of the same staff are involved in the evaluation of emerging design concepts for use in SMRs, more specifically the format and evaluation of supervisor and operator displays that consider generic human factors issues. It is expected that this will provide technical human performance data related to single operator control of multiple reactor units.

The following images illustrate some of the work currently conducted inside and outside the HSSL:

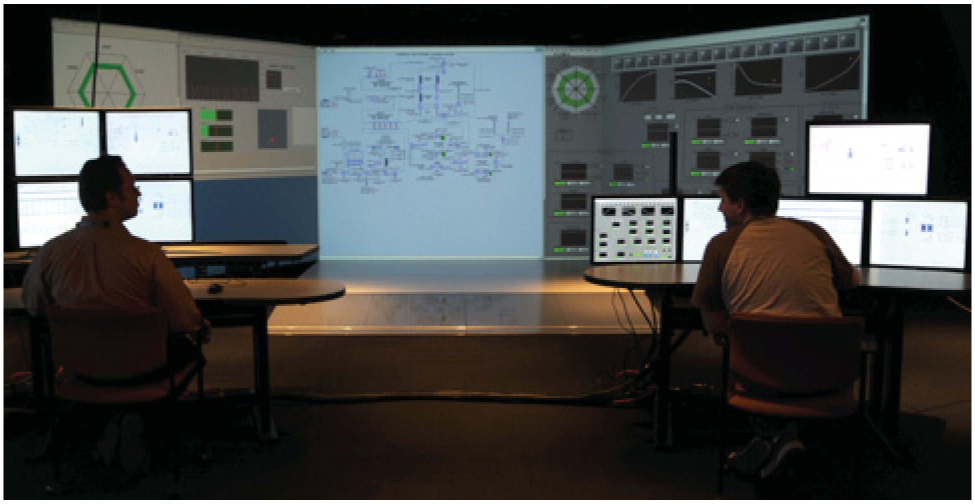

Figure 2: Evaluation of display concepts in the HSSL

Figure 3: Field test of a handheld device first evaluated in the HSSL

Figure 4: Field test of interactive display technology

7 CONCLUSIONS

The DOE has determined the relevance of, and support the INL's vision for establishing a one-of-a-kind reconfigurable simulator that currently houses LWR and SMR design simulations and a variety of smaller generic simulations. Maintaining such a facility is a long term commitment and there is a 10-year plan in place. The lack of empirical knowledge regarding human performance in highly digital control rooms is well recognized and the instantiation of this facility and progress to date indicate that such a facility can go a long way towards meeting the industry and regulatory needs. Specialized needs such as those of the LWRS program are also beginning to benefit from the availability of this facility. In particular, this facility will be able to produce information on failure rates and failures modes associated with human performance in this environment.

Simulation is and remains one of the most cost-effective means by which to assess human performance for situations that are too hazardous to duplicate in the real world. In fact, the cost of errors that may arise from not having such a facility available for the nuclear industry's modernization plans, far outweighs the cost of establishing and maintaining the HSSL. Simulations can be developed quickly and executed under a variety of conditions to determine the nature of human-system response before technology is actually implemented, with the advantage of being less expensive than real world studies. Combined with field studies they can be used to generate data which, in turn, can be used to supplement current design practices and human reliability estimates. Lessons learned from studies conducted can be used to provide insights to industry working groups, the DOE and the Nuclear Regulatory Commission.

The Idaho National Laboratory is a multi-program laboratory operated by Battelle Energy Alliance LLC, for the United States Department of Energy under Contract DE-AC07-05ID14517.

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