INL/CON-10-19524
PREPRINT

The Development of a Human Systems Simulation Laboratory at Idaho National Laboratory: Progress, Requirements, and Lessons Learned

NPIC & HMIT 2010

Katya L. Le Blanc
David I. Gertman
Alan Mecham
William Phoenix

November 2010

The INL is a
U.S. Department of Energy
National Laboratory
operated by
Battelle Energy Alliance

Idaho National Laboratory

THE DEVELOPMENT OF A HUMAN SYSTEMS SIMULATION LABORATORY AT IDAHO NATIONAL LABORATORY: PROGRESS, REQUIREMENTS, AND LESSONS LEARNED

Katya L. Le Blanc*, David I. Gertman, Alan Mecham, & William Phoenix
Idaho National Laboratory (INL)
Idaho Falls, ID 83415
Katya.Leblanc@inl.gov

ABSTRACT

Next generation nuclear power plants and digital upgrades to the existing nuclear fleet introduce potential human performance issues in the control room. Safe application of new technologies calls for a thorough understanding of how those technologies affect human performance and in turn, plant safety. In support of advancing human factors for small modular reactors and light water reactor sustainability, the Idaho National Laboratory (INL) has developed a reconfigurable simulation laboratory capable of testing human performance in multiple nuclear power plant (NPP) control room simulations. This paper discusses the laboratory infrastructure and capabilities, the laboratory' s staffing requirements, lessons learned, and the researcher's approach to measuring human performance in the simulation lab.

Key Words: human systems simulation, human factors, control room development

1 INTRODUCTION

The current administration's commitment to expanding the role of nuclear power in the nation's energy future emphasizes the importance of ensuring that the use of nuclear power is safe, reliable, and economical. Currently, efforts to achieve these goals include activities like efforts to prolong the life of the current fleet of light water reactors (including the implementation of digital upgrades), and the development of advanced reactors including small modular reactors (SMRs) or multi-modular reactors. For example, the DOE budget request for advanced reactor concepts is on the order of $61M [1]. These activities have important implications for human operators in nuclear power plant (NPP) control rooms because they can call for changes in the concept of operations for NPP control rooms (e.g., reduced staffing levels, increased span of control, increased monitoring of automatic functions), they can include changes in the human systems interface (e.g., computerization of operating procedures, implementation of data fusion and higher levels of process abstraction), and they can include changes in the amount of automation used in control rooms (higher degrees of automation and presence of mixed initiative systems). In short, the digitization and advancement of NPP control room designs has the potential to dramatically change the human operator's role in control room operations, how s/he interacts with the control system, and the level of operator and crew involvement in control room operations.

These potentially significant changes for the human operator in NPP control rooms give rise to an increasing importance in developing effective methods and research programs for investigating human performance issues in NPP control rooms. Ideally, regulatory decisions, licensing decisions, and design decisions should be made on the basis of empirical studies that have established cause-and-effect relationships between important design factors, system performance, and human performance. Evaluating human performance for NPP control room conditions s is associated with a number of challenges including duplicating expected conditions for known off normal and emergency events or yet unforeseen events, duplicating the time available for operator and crew response, finding representative test subjects, and characterizing the nature of human response associated with human interaction with advanced digital systems. The simulator has proven itself to be a powerful tool for duplicating plant conditions of interest and evaluating operator response. However, simulation systems are complex, expensive, may have limited availability, and often it is difficult to obtain operators to use as subjects. When conducting research under the conditions mentioned above, there is often a trade-off between ecological validity (the degree to which experimental results can generalize to the real-world control room situation) and the experimenter's degree of laboratory control.

Researchers in the nuclear arena tend to sacrifice laboratory control in order to maximize ecological validity, favoring descriptive methods like observation in naturalistic settings. For example, a popular approach is to collect observational data on human performance during training scenarios on full-scope simulators. When research is conducted this way, it is difficult for experimenters to control many of the factors that would allow them to draw causal conclusions between the factors being studied, which, in turn, limits the strength with which researchers can make recommendations for licensing, regulatory, and design decisions.

Unfortunately, the cost of the full-scope simulators used in NPP training is often prohibitively expensive for researchers to purchase for experimental studies. In addition, obtaining a single full-scope simulator for research may limit research findings to that particular type of plant and would not allow for the testing of upgraded systems without expensive changes to the simulator. Researchers at the INL are finalizing a Human Systems Simulation (HSS) Laboratory that will bridge the gap between laboratory control and ecological validity. The HSS lab at INL, supported by the US Department of Energy, is designed to be reconfigurable so that conceivably, any NPP control room can be simulated. The HSS lab will focus on advanced designs like multi-modular reactors in order to address the industry's need to have empirical data on human factors issues related to these advanced designs and to further our understanding of human performance and safety in these environments. Our objectives are as follows:

Objectives:

1. Develop the laboratory infrastructure for a reconfigurable control room that can simulate current, hybrid, and advanced control room designs.
2. Develop the staff and expertise to design scientifically rigorous studies that address current and relevant human performance issues in the nuclear industry.
3. Develop a comprehensive set of objective measures including the use of physiological equipment like eye trackers, galvanic skin response, breathing monitors, and electrocardiographs that can be used to measure human performance in a wide variety of simulated control room tasks.

This paper summarizes our approach to developing the advanced reconfigurable HSS laboratory, our progress in developing this laboratory, and lessons learned.

2 LABORATORY INFRASTRUCTURE

The HSS lab is currently equipped with several computer workstations, each providing a portion of for the labs specific capability. The laboratory can be configured to represent multiple operator workstations with a variable number of displays dedicated to each workstation. In addition, the laboratory has several ways to present large screen overviews in the simulated control room. The HSS laboratory currently has two NPP simulations and is capable of running other NPP simulations as they become available. Human performance data can be collected in multiple ways including an array of physiological equipment and audio/video recordings of experimental sessions. The details the laboratory set up and equipment are listed below.

2.1 Hardware/Equipment

Two operator workstations are each equipped with a 2.66Ghz Xeon based Dell Precision workstation, with dual 4 channel NVIDIA Quadro NVS 450. Each workstation is equipped with four twenty one inch flat panel LCD monitors with the capability to expand to up to eight 21" monitors or eight 30" monitors if necessary.

Another workstation is designated for driving the large screen overview display which is currently displayed on an 82" Mitsubishi 3d enables high-definition television. The large screen overview can also be displayed on the CAVE with which the HSS lab shares space (see below for more information on the CAVE).

The faceLAB™ eye-tracking system, consisting of a Core 2 Duo based Dell laptop running windows Vista and two infrared cameras pods are available on each operator workstation to provide data on gaze, blinking, and areas of concentration.

A fourth workstation is designated to the recording of audio and video for review, and coding of behavioral data; it is also used for the recording of physiological data collected from the BioPack™, a system consisting of a transmitter and receiver that hooks into the electrodes used to gather respiration, galvanic skin response, and heart rate data via electro-cardiogram.

Four Sony EVI-D70 Cameras are positioned around the operators, providing over the shoulder views or environment overviews as desired. Using lightweight low profile camera stands provides quick setup and reconfigurable functionality. Coupling the easy to move physical locations with the remote zoom and panning feature that the camera enables getting desired views to be relatively easy.

To complement the individual computer workstations, the HSS Laboratory shares space with a Mechdyne Flex CAVE immersive environment. The HSS lab has the ability to interface with each of the three walls of the CAVE displaying any information for the workstations on a wall of the CAVE. One of the many features that this CAVE system affords us is the ability to open the side walls to a full length 30 foot large display additionally the side walls can be stopped at any position in between the fully open configuration and fully closed one, allowing for a horse-shoed control overview layout to be tests. The flexibility provided makes it an ideal system to use for displaying plant wide overviews, digital panel tests and other control room instrumentation.

See Figure 1for an example of the laboratory layout.

Figure 1. The HSS lab in one configuration.

2.2 Simulation Software

The HSS lab is equipped with two simulations including a fully interactive digital rendering of a mid 1980's vintage hybrid analog/digital control room for a PWR and a plant model for an advanced small modular reactor. Each simulation is equipped with its own proprietary software development environment that allows for design of display and alarm overviews. Each of the systems allows for plant malfunctions to be controlled by the experimenter and a flexible event logging system.

2.3 Other Software

Human factors data collection includes on-line collection and analysis of physiological data (heart rate, galvanic skin response, breathing, eye gaze) using the AcqKnowledge ™ software. The video recordings and physiological data are imported into Noldus Observer XT software, which time synchs the physiological recordings with the video recordings. The Noldus Observer XT software also provides the capability to playback video and audio recordings of experimental sessions and the ability to code behaviors in real time or during playback.

3 STAFF AND EXPERTISE

To support collection of reliable human performance data in the reconfigurable simulator, the HSS lab employs a multidisciplinary staff with characteristics described below.

3.1 Human factors staff

The HSS laboratory needs to have a full-time human factors expert who is trained in experimental design, statistics, and human performance measurement. In addition, the human factors expert must also be trained to have a basic understanding of the NPPs that are simulated in the laboratory and a basic understanding of control room operations so that he or she can help to plan controlled and realistic experimental scenarios.

3.2 Technical Staff

The HSS lab needs to have a full-time technical staff that can 1) Install and maintain all hardware and software that is required for the lab 2) Develop and implement changes to the human systems interface for the simulations as needed by the experimental goals defined by the specific issues the lab is currently investigating.

3.3 Support Staff

The HSS lab also needs continuous access to experts in the nuclear field including: mechanical and nuclear engineers who understand the design and operation of the specific plants, control room operators with an understanding of conduct of operations for NPPs during normal, abnormal and emergency conditions, and I&C experts who understand the operational requirements for upgraded hybrid control rooms.

3.4 Participants

For existing plants, the HSS needs to have access to licensed operators who can serve as participants in experimental studies. This cannot be over emphasized, design engineers have a different perspective than end-users and many studies suffer from using experimenters and designers rather than end-users. For advanced plants, the HSS lab needs to have access to operators who understand basic issues related to plant operations (e.g., thermodynamics and reactor physics) and who can be trained in the functioning and concept of operation for a specific plant simulation.

4 MEASURES OF HUMAN PERFORMANCE

One challenge associated with collecting data in NPP control room simulators is the issue of how to measure human performance. Experimental results must have relevance to real world control rooms. Many of the methods currently employed in studies investigating human performance in the nuclear industry are subjective and qualitative. For example, many studies have employed the use of expert observation to collect data on human performance [2, 3, & 4]. While expert observation can provide valuable information on operator performance, we feel that it is desirable to use methods that are objective and quantifiable to measure human performance in simulator studies.

A review of the research that has utilized NPP control room simulations reveals a variety of methods used to measure human performance. Researchers have measured performance objectively using errors [5, 6, 7, & 8] response times [6, 7, 8, 9, 5, & 10] physiological correlates of performance [11, 12, & 13], and subjectively using self report techniques [11, 14, 12, 13, 10, & 5].

The HSS lab is using a combination of these methods focusing on the collection of objective performance data logged by the simulation software (including tracking plant parameters, alarms, operator control actions, and operator response times) and the continuous collection of physiological data that is known to correlate with human performance issues like mental workload, situation awareness and fatigue. The specific methods the HSS lab will employ are listed below

4.1 Eye Tracker

Researchers in the HSS lab will use eye tracking systems to measure situation awareness and workload. Workload will be measured via blink rate and blink duration. Both blink rate and blink duration decrease with increasing mental workload [15 & 16].

Eye tracking will also be used to measure situation awareness by assessing gaze patterns. Situation awareness can be assessed by measuring an operator's anticipation of an event by determining whether he focuses his gaze in the direction where relevant information will be displayed [17]. Situation awareness can also be measured by measuring an operator's gaze pattern and duration of fixation [18].

4.2 Electrocardiogram

Researchers will use electrocardiogram (ECG) to measure heart rate. Previous research shows that heart rate increases as mental workload increases [19]. In addition to heart rate, heart rate variability has been shown to indicate changes in mental workload [20].

4.3 Respiration

Researchers will use respiration cycle time to measure cognitive workload. Previous research has shown that cycle time decreases as cognitive workload increases [16].

4.4 Galvanic Skin Response

Preliminary research has shown that mean GSR increases with increasing cognitive load [21]. Researchers in the HSS lab will use mean GSR to measure cognitive load.

4.5 Plant Performance

Researchers will track plant parameters (e.g., pressurizer pressure, reactor power, etc.) and compare them to the ideal parameter for a given simulation scenario. A mathematical formula described by Ha, et al. [11], gives the overall deviation in plant parameters. This measure allows for the quantification of plant performance which combines human performance and system performance into one measure.

4.6 Operator and Crew Performance

Operator and crew performance will be measured with response times and errors. Response times will be defined as time to detect malfunctions, time to diagnose malfunctions, time to initiate procedures and time to complete a scenario. Errors will be defined in the context of the current scenario. Definitions of errors could include the following: incorrect control action, deviation from an ideal sequence of actions, omission of a procedure step, *et cetera*.

4.7 Self Report Techniques

Workload and situation awareness will also be measured subjectively using self report techniques. Workload will be assessed using the NASA Task Load Index [21]. Situation awareness will be measured with a survey developed by INL staff and using the Situation Awareness Control Room Inventory [22]. Self report techniques will be compared to objective measures of workload and situation awareness to determine the degree to which they correlate.

5 LESSONS LEARNED

5.1 Simulation Software

We have conducted two small pilot studies using the simulation of the hybrid analog/digital control room and have determined that in order to maximize the ability to collect performance data during experimental scenarios, simulation software needs to meet a number of minimum requirements relating to the experimenter's ability to access important plant data and to control plant conditions. Simulation software needs to have the capability to:

1. Log time stamped systems parameters and output them into a text file
2. Allow the experimenter to choose which of the system parameters to log
3. Log operator actions and output them into a time stamped text file
4. Synch physiological equipment with the simulation software
5. Log time stamped simulation events such as alarms, trips, and malfunctions and output them into a text file
6. Set initial conditions easily
7. Easily inject plant malfunctions and have them carried out automatically
8. Efficiently change display parameters so that new designs can easily be tested

5.2 Time synching of simulation with peripheral equipment

In order to accurately monitor an operator's reactions (behavioral and physiological) to simulation events, it is important to ensure that the simulation software is precisely time-synched with peripheral equipment such as video recording, audio recording, and the physiological equipment. Physiological reactions such as changes in heart rate, respiration, or skin conductance occur on very short time intervals. In order to effectively correlate those reactions to events, occurring in the simulation scenario, it is important to make sure that the timing of both systems is perfectly synched.

5.3 Allow proper lead time for equipment purchase and integration

One of the lessons we were taught multiple times was that it always seems to take longer than you first expect to procure, inspect, install, and test hardware and software necessary for properly equipping the simulator facility. In our case we, are located within the Center for Advanced Energy Studies (CAES) in Idaho Falls and we had to coordinate installation with the CAES facility as well as through our own procurement system. We imagine that this is the experience of others in standing up simulator facilities and performing Government research.

5.4 Identify and maintain key personnel

Although it seems obvious, resources must be made available to assign and retain personnel key to the simulator operation. There is a certain amount of familiarization needed on the part of everyone regarding the functioning of the simulator and understanding of its capabilities and limitations.

6 CONCLUSIONS

The safe operation of NPPs has relied upon the skill of licensed control room personnel, the proper functioning of safety systems, and risk management and regulatory practices. Historically, NPP simulators have been used to support the training of control room operators and to sharpen their skills in diagnosing and mitigating failures by following plant procedures. However, additional uses for the simulator exist as well. Digital upgrades and advanced plant designs require a thorough understanding of the human performance issues related their design. Using simulators, issues like increasing automation and advanced display concepts need to be tested in scientific experiments in order to ensure their safe implementation. The development of the HSS laboratory at INL will provide the nuclear industry with an excellent place to perform these studies because of the flexibility of the design to model many control rooms, and for the ability to exert an appropriate amount of laboratory control while still maintaining a high degree of ecological validity in the laboratory. In addition, the development of a comprehensive set of objective performance measures that researchers can use in the laboratory will ensure that regulators and industry alike can have confidence in the results obtained in the HSS lab.

7 DISCLAIMER

8 REFERENCES

1. R. Black, "DOE Programs for Small Modular Reactors and Advanced Reactor Conference", *Platts Small Modular Reactor Conference (SMR)*, Washington DC, July 12-13 (2010).

2. P.V.R., Carvalho, “Ergonomic field studies in a nuclear power plant control room”, *Progress in Nuclear Energy*, **48**, pp. 51–69 (2006).
3. E. Roth, & J. O'Hara, “Integrating digital and conventional human system interface technology: Lessons learned from a control room modernization program (NUREG/CR-6749)” Washington, D.C.: U.S. Nuclear Regulatory Commission (2002).
4. F. Jeffroy, & S. Charron, “From safety assessment to research in the domain of human factors: The case of operations with computerised procedures.” *IEEE 6th annual Human Factors Meeting*, Orlando FL (1997).
5. S. Converse, “Evaluation of the Computerized Procedure Manual II (COPMA II) (NUREG/CR-6398)”, Washingtion, DC: U.S. Nuclear Regulatory Commission (1995).
6. S. Xu, F. Song, Z.Z. Li, Q.Y. Zhao, W. Luo, X.H. He, & Salvendy, G., “An ergonomics study of computerized emergency operating procedures: presentation style, task complexity, and training level”, *Reliability Engineering and System Safety,* **93** (10), pp. 1500–1511 (2008).
7. F.-H. Huang, & S-L. Hwang, “Experimental studies of computerized procedures and team size in nuclear power plant operations”, *Nuclear Engineering and Design.* **239***,* pp. 373–380 (2009).
8. E. Lois, V.N. Dang, J. Forester, H. Broberg, S. Massaiu, M. Hildebrandt, P. Ø. Braarud, G. Parry, J. Julius, R. Boring, I. Männistö, & A. Bye, “*International HRA empirical study—Phase 1 report, Description of overall approach and pilot phase results from comparing HRA methods to simulator performance data,”* NUREG/IA-0216, Vol. 1. US Nuclear Regulatory Commission,Washington, DC (2009).
9. Y. Lee, S. Hwang, & E. Wang, “Reducing cognitive workload of a computer based procedure system.” *International Journal of Human-Computer Studies,* **63,** pp. 587-606 (2004).
10. B.P. Hallbert, A. Sebok, & D. Morrisseau, & U.S. Nuclear Regulatory Commission. Office of Nuclear Regulatory Research. & OECD Halden Reactor Project, “*A study of control room staffing levels for advanced reactors”* Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, Washington, DC, (2000).
11. J. S. Ha, P.H. Seong, M.S. Lee, & J.H, Hong, “Development of human performance measures for human factors validation in the advanced MCR of APR-1400”, *IEEE Transactions on Nuclear Science* **54** (6) pp. 2687–2700. (2007).
12. F.-H. Huang, S.-L., Hwang, T.-C. Yenn, Y.-C. Yu, C.-C. Hsu, & H.-W Huang, “Evaluation and comparison of alarm reset modes in fully digital control room of nuclear power plants.” *Safety Science*, **44**, 935–946. (2006).
13. S.-L. Hwang, Y.-J Yau, Y.-T Lin, J.-H Chen, T.-H Huang, T.-C Yenn, C.-C. Hsu, “Predicting work performance in nuclear power plants”, *Safety Science*, **46 (7)**, pp. 1115-1124 (2008).
14. A. Sebok, “Team Performance in Process Control: Influence of Interface Design and Staffing Levels”, *Ergonomics*, **43** (8), 1210-1236 (2000).
15. J. B. Brookings, G. F. Wilson, & C. R. Swain, “Psychophysiological responses to changes in workload during simulated air traffic control.” *Biological Psychology,* **42***,* pp. 361-377. (1996).

16. J.A. Veltman, A.W. Gaillard, “Physiological workload reactions to increasing levels of task difficulty”, *Ergonomics*, **41,** pp. 656–669 (1998)

17. G. Hauland, “Measuring team situation awareness by means of eye movement data”, *Proceedings of HCI International 200,* **3**, pp. 230-234. Mahwah, NJ: Lawrence Erlbaum Associates. (2003).

18. G. Hauland, “Measuring Individual and Team Situation Awareness During Planning Tasks in Training of En Route Air Traffic Control”, *The International Journal of Aviation Psycholog*y, **18**(3), 290 -304 (2008).

19. T. C. Hankins , & G. F. Wilson, “A comparison of heart rate, eye activity, EEG and subjective measures of pilot mental workload during flight”, *Aviation, Space, and Environmental Medicine,***69***,* 360–367 (1998).

20. N. Hjortskov, D. Rissen, A.K. Blangsted, et al. “The effect of mental stress on heart rate variability and blood pressure during computer work.” European Journal of Applied Physiology , **92,** pp. 84–89 (2004).

21. Y. Shi, N. Ruiz, R. Taib, E. Choi, & F. Chen, “Galvanic skin response (GSR) as an index of cognitive load”, *CHI '07 Extended Abstracts on Human Factors in Computing Systems,* pp. 2651-2656. ACM, New York, NY (2007).

22. S. G. Hart, & L. E. Staveland, “Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research”, *Human Mental Workload.* Elsevier, Amsterdam, the Netherlands (1988).

23. D. N. Hogg, K. Folleso, F. Strand-Volden, & B. Torralba, “Development of a Situation Awareness Measure to Evaluate Advanced Alarm Systems in Nuclear Power Plant Control Rooms,” *Ergonomics,* **11**, pp. 394-413 (1995).