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Abstract: In this paper, we propose a method to improve the data basis of human reliability analysis (HRA) by extending the data sources used to inform HRA methods. Currently, most HRA methods are based on limited empirical data, and efforts to enhance the empirical basis behind HRA methods have not yet yielded significant new data. Part of the reason behind this shortage of quality data is attributable to the data sources used. Data have been derived from unrelated industries, from infrequent risk-significant events, or from costly control room simulator studies. We propose a benchmark of four data sources: a simplified microworld simulator using unskilled student operators, a full-scope control room simulator using skilled student operators, a full-scope control room simulator using licensed commercial operators, and a human performance modeling and simulation system using virtual operators. The goal of this research is to compare findings across the data sources to determine to what extent data may be used and generalized from cost effective sources.

Keywords: HRA, control room simulator, simulation, microworld

1. INTRODUCTION

It is well established that the human contribution to the risk of operation of complex technological systems is significant, with typical estimates lying in the range of 60-85% (Trager, 1985). The human operator of a nuclear plant can contribute to risk through acts of both omission and commission. In particular, complex commission errors have been a contributor to many significant catastrophic technological accidents. The most well known example in the nuclear industry is perhaps the termination of safety injection during the Three Mile Island (TMI) accident (Kemeny et al., 1979).

Human reliability analysis (HRA), a component of an integrated probabilistic risk assessment (PRA), is the means by which the human contribution to risk is assessed, both qualitatively and quantitatively. HRA as a discipline has as its goals the identification, modeling, and quantification of human failure events (HFE) in the context of an accident scenario. Analysts have included assessments of human reliability in military system safety evaluations since the 1960s (Swain, 1963), but the first widely publicly available guidance for HRA was described in the WASH-1400 report (U.S. Nuclear Regulatory Commission, 1975), which addressed the safety of nuclear power plants in the U.S. *The Technique for Human Error-Rate Prediction* (THERP; Swain and Guttman, 1983), which evolved from the HRA performed for WASH-1400, provided the first systematic method of identifying, modeling, and quantifying human errors, and is viewed as the parent of HRA methods today.

At the time THERP was published, HRA as a discipline was barely beyond its infancy. A generation later, there are literally dozens of HRA methods to choose from. However, many difficulties remain. A principal difficulty, and one that hampers use of HRA results in risk-informed decision-making, is the large variability associated with the analysis results, from one method to another, and between analysts for a given method. This was a difficulty first highlighted by the so-called Ispra study of 1989 (Commission of the European Communities, 1989), in which four orders of magnitude were observed among the estimates of human error probability developed by teams analyzing a common benchmark problem. The more recent international HRA empirical study, sponsored by the U.S. Nuclear Regulatory Commission, has found that, twenty years after the Ispra study was published, large variability appears to remain (U.S. Nuclear Regulatory Commission, 2009). One explanation for this variability is a lack of solid empirical basis in HRA methods, potentially resulting in poor mapping of situations to the modeling capabilities of individual HRA methods and their quantification mechanisms.

2. EXPERIMENTAL FRAMEWORK

One of the persistent challenges of HRA remains how to obtain enough data to understand human performance. Especially given HRA's strong foundations in nuclear energy, the opportunity to build up an extensive corpus of human performance data is difficult given the complexity and cost of studies involving nuclear power plant operators. Database efforts such as NUCLARR (Gertman et al., 1990) and HERA (Hallbert et al., 2006) have attempted to look at nuclear power analyses and events as a means of expanding the data basis in HRA. This approach has thus far proved inadequate to significantly expand the data underlying HRA. In the case of NUCLARR, event analyses were built on other event analyses, and the database became too circular to prove a robust data source. Work on HERA is ongoing, but the events analysed in HERA are too infrequent to provide quantitative insights in the form of human error probabilities. Chang et al. (in press) have devised a method to elicit data from training scenarios in control room simulators, which may prove an effective way to gain human performance data below the threshold of reportable events. Tran et al. (2007) and Griffith and Mahadevan (2011) have suggested the use of meta-analytic techniques to generalize data. This approach was incorporated into the NASA HRA database (Boring et al., 2006), which features a taxonomy that allows HRA insights to be gleaned from multiple sources, including traditional human factors studies outside the aerospace or nuclear domains. A similar approach for generalizing results is used in the CORE-DATA (Gibson, Basra, and Kirwan, 1999), in which human performance insights are extracted from multiple domains. The CORE-DATA serves as the underlying data basis for the NARA and CARA HRA methods, among others still in development. Generalizing data from different sources to nuclear power operations is also the key idea in Jing, Lois, and James (2011), which provides a preliminary framework for mapping human errors across domains.

The research framework presented in this paper builds on prior efforts to create a solid data basis for HRA by investigating the opportunity for data collection from multiple sources. Table 1 lists the types of experimental environments currently being coordinated as part of this research. The aim of this research is to bridge different capabilities at several research facilities, each with a shared goal to produce insights into human performance that can inform HRA. Following is a brief discussion of each research area prior to a discussion of the synthesis of the separate projects in Section 3.

Table 1. Crosswalk of Different Research Platforms for HRA

Title	Microworld	Generic Simulator	Training Simulator	Simulation
Location	University of Idaho	Ohio State University	Idaho National Laboratory	University of Maryland
Apparatus	Low fidelity simulator of process control	Full-scope boiling water reactor simulator	Full-scope pressurized water reactor simulator	Virtual operation and operator model
Participants	University students with minimal training	University students with formal training	Licensed operators	Virtual operators
Interface	Simplified graphical user interface	Enhanced plant interface with advanced overview displays	Digital mimics of analog instrumentation and controls	Interface to plant model and thermal-hydraulics through software
Metrics	Primarily performance data (e.g., reaction times and accuracy) automatically logged through experimental trials	Observational performance logging coupled to simulator logs; crew debriefs	Observational performance logging coupled to simulator logs; crew debriefs; physiological measures; eye tracking	Performance over repeated trials, typically in the form of success/failure metrics and timing
Advantages	Ability to run large number of experiments suitable for inferential statistics and first principles research	Authentic plant model; ability to run large number of student operators; flexibility to incorporate new interface elements	Authentic plant model identical to one used for operator training	Ability to run unlimited simulations within the constraints of what can be modelled in the system
Limitations	Limited fidelity of simulator; limited expertise of student participants; constrained ability to study team collaboration due to solo participant interface within microworld	Some limitations of student crew training and experience—it is unrealistic to test student operator performance on certain complex scenarios for which they do not have same versatility as licensed crews	Limited availability of licenced operators for experimental work; because of complexity of plant control, difficult to control for confounds in operations such as multiple faults resulting from a faulted system	The fidelity of the simulation is limited by the quality and completeness of the underlying modeling of the system; considerable development effort to incorporate new features and scenarios

2.1 Microworld Simulator

Microworlds are a type of simplified simulation that allows users to learn about the domain being simulated. They differ from simulators, which generally strive for maximum realism. Whereas users must generally be extensively trained to operate simulators, microworlds are often software tools built to help the users understand the concepts and build up an understanding with minimal training. Whereas an electrical grid simulator might offer a realistic model of electrical distribution including an interface that directly mimics the real control system interface that grid controllers would use, a microworld would feature a simplified model and interface designed to help the would-be controller understand the fundamental concepts of grid control. In many cases, microworlds provide the opportunity for training on the interaction between different stakeholders in a complex system environment. This is, however, not a strict requirement of microworlds, and successful microworlds may also feature a single user.

In the context of HRA for nuclear power plants (NPPs), there is a need for more flexible, varied, and expedient research studies than are possible in a full-scope nuclear power plant simulator. A microworld simulator fulfills this requirement by providing a simplified, readily adaptable model to which non process experts can be trained. Microworlds such as the Dual Reservoir System Simulator (DURESS; Orchanian et al., 1996) even allow students to be trained to functionally equivalent tasks to those that might be performed in NPPs. The microworld, because it is not tied to a specific plant model, can be customized in a way that real-world plant models cannot while still affording the opportunity to simulate the complex multitasking that is present in real-world control rooms. These results from microworld experiments should not, of course, be generalized back to NPP control rooms without validation. One purpose of the proposed research is to have a validation exercise between a microworld simulator study developed at the University of Idaho (UI) and the equivalent full-scope research simulators at Idaho National Laboratory (INL) and Ohio State University (OSU).

2.2 Simulators

Simulator technology for domains such as aviation emerged in the 1930s with the invention of the Link Trainer, a device that allowed pilots in training to learn to manipulate flight controls in a rudimentary manner (Robertson Museum and Science Center, 2000). It was not until considerably later—with advances in computing technology—that mathematical system models and computer generated imagery could be harnessed to create realistic, virtual flight simulations. A similar course was followed for nuclear power plants—initial non-operational hardware mockups of control room panels gave way to entire control room simulators with functional control panels interfaced with underlying thermal-hydraulic code. Nuclear power plant simulators evolved from being static training representations to interactive, operational systems that could be used to train and test reactor operators' knowledge of plant states and scenarios.

A 2004 report by the International Atomic Energy Agency (IAEA, 2004) 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.

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.

The term *training simulator* is synonymous with a full-scope simulator as would be found at a nuclear power plant. All simulator types may be used as part of an effective training regime, but there have been increased emphasis on and requirements for training in full-scope simulators. The considerable demand on plant training simulators was already evident in 1992 (Institute of Nuclear Power Operators), when a survey 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. As such, control room simulators have been created separate from plants, to serve the primary purpose to conduct research, not to train reactor operators. These are *research simulators*.

While striving to create a realistic plant environment for operators, a research control room simulator provides the opportunity to design and validate new hardware and plant models. New hardware and plant models may prove difficult to implement in training simulators, which are closely tied to the actual plant. This reconfigurable aspect of research simulators affords a unique opportunity to test actual human operators. A significant advance of incorporating human-in-the-loop testing is the ability to estimate the safety of novel control room equipment and configurations. Such a control room simulator serves an emerging research need to collect data on operator performance using new control room technologies. Moreover, it can serve to provide an empirical basis for human reliability modeling used in the certification of plant safety.

A full-scope plant simulator comprises several layers of systems as depicted in Figure 1. 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 L3), 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 human-system interface (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 and development simulators. Digital soft control systems may take the form of mimics to analog plant instrumentation and control (I&C) or may represent advanced I&C that incorporates features such as overview displays and information rich trending displays.

The OSU Risk and Reliability Lab is in the process of developing a full-scope control room and plant simulator (see Figure 2) based on a Boiling Water Reactor 4 design. The simulator will be a complete mockup of a control room, providing an experience for student operators that is functionally equivalent to operating a real plant, with the distinction that advanced HSI elements will be incorporated into the control room. The participants of the training and experiments will be able to respond realistically to equipment malfunctions and major plant upsets that may be anticipated, so that they are aware of the actions to be taken. The simulator will be a vital tool in support of this research.

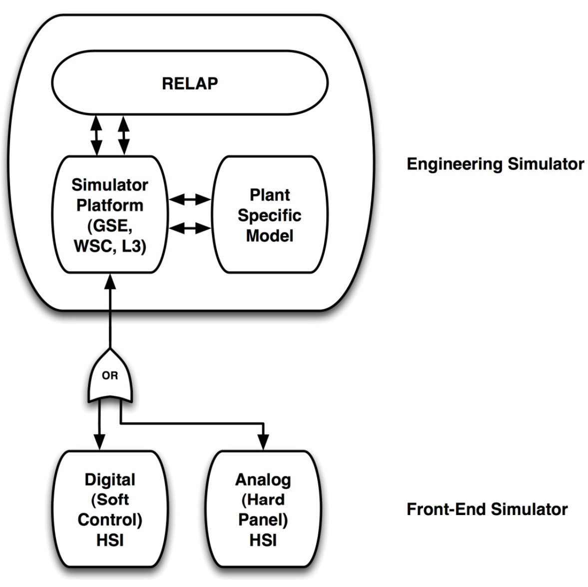

Figure 1. The Different Components of a Plant Simulator

Figure 2. Planned Simulator Facility in the OSU Risk and Reliability Laboratory

Figure 3. Planned Human-System Simulation Laboratory at the INL

The INL Human-System Simulation Laboratory (see Figure 3) is a platform- and plant-neutral environment intended for full-scope and part-task testing of operator performance in various control room configurations. Currently, plant-specific simulators are coupled to the existing configuration of the plant and are impractical or difficult to reconfigure to test new designs. The INL facility is not limited to a particular plant or even simulator architecture. It currently supports engineering simulator platforms from multiple vendors using digital interfaces. With reconfigurability, it is possible to switch the I&C—not just to digital panels but also to different control modalities such as those using greater plant automation or intelligent alarm filtering. Current efforts are centered around building out a Combustion Engineering full-scope simulator that is an exact digital replica of the plant control room. The intent is that licensed plant operators will be able to use the facility as a research simulator, because there is limited availability of the plant training simulator.

Both the OSU and INL simulators will be complete in the Summer of 2012.

2.3 Human Performance Modeling and Simulation

Cacciabue (1998) and others (e.g., Lüdke, 2004) have outlined the importance of simulation and modeling of human performance for the field of human reliability analysis (HRA). Specifically, simulation and modeling address the dynamic nature of human performance in a way that has not been found in most HRA methods. Concurrent to the emergence of simulation and modeling, several authors (e.g., Jae & Park, 1994; Sträter, 2000) have posited the need for dynamic HRA and have begun developing new HRA methods or modifying existing HRA methods to account for the dynamic progression of human behavior leading up to and following human failure events (HFEs). Currently, there is interest in the fusion of simulation and modeling with HRA (e.g., Mosleh & Chang, 2003; Boring, 2007).

It is important to note a key distinction here between *simulation* and *simulator* data. Simulations utilize virtual environments and virtual performers to model the tasks of interest. In contrast, simulators utilize virtual environments with human performers (Bye et al., 2006). In most cases, simulations and simulators may both be used to model dynamic human performance and reliability, as both produce a log of performance over time and tasks. Because simulators use real humans, it is possible to capture the full spectrum of human performance for a given task, whereas simulations must rely on those performance metrics that can be modeled virtually. However, simulations afford the opportunity to perform a wider spectrum of modeling and typically allow easier and more cost effective repeated trials than those tasks involving humans. A large number of trials involving actual humans in simulators is possible but typically requires seeding or forcing an error likely situation in the simulator runs, which may prevent a high level of scenario realism.

Human performance simulation utilizes virtual scenarios, virtual environments, and virtual humans to mimic the performance of humans in actual scenarios and environments. What sets this form of HRA apart is that it provides a dynamic basis for HRA modeling and quantification. Traditional HRA methods, by any definition, have featured largely static task analyses of operating events as the underlying basis of performance modeling. These methods have also relied on performance estimations mapped to similar previous performance derived through empirical data or expert opinion. Simulation-based HRA differs from its antecedents in that it is a dynamic modeling system that reproduces human decisions and actions as the basis for its performance estimation. Simulation-based HRA may utilize a frequentist approach for calculating HEPs, in which varieties of human behaviors are modeled across a series of Monte Carlo style replications, thus producing an error rate over a denominator of repeated trials. Simulation-based HRA may also augment previous HRA methods by dynamically computing performance shaping factor levels to arrive at HEPs for any given point in time.

Meister (1999) suggests that human reliability analysis (HRA) filled an important void early in the evolution of human factors by centering on prediction. Much of classic human factors has centered on the collection of data on the interaction of humans with designed systems. The purpose of such data is to improve the design of the system, ultimately to optimize human performance in terms of criteria such as usability, efficiency, or safety. HRA has instead attempted to predict human performance, specifically human errors, that can occur in such human-machine interactions. The purpose of HRA is therefore not typically to improve the design of the system so much as to determine what factors impact the safe human operation of that system. Over time, HRA has been joined by another predictive tool, namely human performance modeling. Human performance modeling is an umbrella term used to describe systems that simulate human decision making and actions. Human performance modeling is largely synonymous with cognitive simulation and artificial intelligence, although it has in practice applied to unified systems that attempt to account for a broad range of human cognitive activities. In contrast, variants of cognitive simulation or artificial intelligence may focus on modeling specific cognitive mechanisms instead of providing integrated models of multiple cognitive mechanisms. This distinction is analogous to the differences found in hardware component vs. system models, respectively.

The University of Maryland (UMD) has for some time been exploring the development of dynamic HRA models, models that rely on the simulation capabilities provided by today's computing power. The efficacy of the dynamic HRA models is dependent on creating a realistic, psychologically grounded model of crew performance. UMD's Accident Dynamics Simulator-Information Decision and Action in Crew (ADS-IDAC) system was developed specifically for HRA applications, tying together a cognitive model, a decision making engine, performance shaping factors, and a dynamic event simulator (Smidts et al., 1997; Chang and Mosleh, 2007) .

As noted by Gore and Smith (2006), the human performance modeling and simulation systems used in the mainstream human factors community have not addressed HRA. With the exception of ADS-IDAC, research on tying human performance models to HRA is preliminary. Because ADS-IDAC is the only human performance modeling system specifically designed for nuclear power plant applications and because it is also the only system specifically designed to model human error and produce human error probabilities, ADS-IDAC is being used in this project. While other human performance modeling and simulation systems have achieved an otherwise adequate level of maturation in their domains, only the ADS-IDAC system requires minimal extensions to be used for HRA in nuclear power. Extending other human performance modeling systems to include HRA would require costly and time-consuming extensions. Thus, instead of first modifying a system to enable it to support HRA, selection of ADS-IDAC permits immediate development efforts to be tied to extending its HRA capabilities.

Because the ADS component of ADS/IDAC is a proprietary mapping of IDAC to thermal-hydraulic code, IDAC will be decoupled from ADS and coupled to the simulator. This will allow IDAC to be used for a wider variety of applications.

3. AN INTEGRATED FRAMEWORK

The three separate data generation methods discussed in Section 2—microworlds, simulators, and simulation—come together in an important way in this project. All three data sources represent different ways of capturing HRA-relevant data (see Table 1):

- Microworlds allow large scale data collection using simplified process control.
- Simulators allow high fidelity data collection using skilled operators.
- Simulation allows generation of virtual performance data based on specified parameters.

To date, the most widely espoused method of collecting data for HRA has been from simulator data, similar to the full-scope simulator with licensed operators at INL. However, the fiscal and practical constraints of running large numbers of crews across large numbers of scenarios suggests this approach will not yield significantly more data than has been generated since HRA's inception. The other three data sources identified in this paper do hold the promise of being more economical and more feasible:

- Microworlds such as DURESS at UI can be run inexpensively using university students as operators on simplified tasks.
- The research simulator at OSU features a cohort of Nuclear Engineering students who are emerging subject matter and operations experts.
- The ADS/IDAC simulation platform at UMD offers literally limitless virtual operator runs to identify potential human performance issues.

The problem is that none of these alternative data sources feature actual operators in actual control rooms. As such, the quality and generalizability of the findings may seem limited in terms of their application to

HRA for nuclear power. Tasks are being identified that may prove comparable across the different experimental platforms. The *Boiling Water Reactor and Pressurized Water Reactor Off-Normal Event Descriptions* (NUREG-1291; U.S. Nuclear Regulatory Commission, 1987) is being reviewed to find common scenarios that can be run on both the OSU and INL simulators and that can be simplified to run in the UI microworld environment. Similarly, candidate scenarios will be coded into ADS/IDAC to compare the virtual operator performance against unskilled student operators at UI, skilled student operators at OSU, and licensed commercial operators at INL.

The key to understanding the similarities and differences between the data sources is to benchmark them against each other using similar scenarios. Candidate simulator scenarios will be identified (e.g., station blackout), and the simulator environments and simulation will be configured to run an example scenario in 2012. Research will be performed to develop questionnaires capturing the operators' mental state at the onset of the simulator run as well as non-observable performance shaping factors at the end of the simulator run.

Additional studies are planned for 2013, using the simulator facilities at the INL and OSU as well as the microworld environment at UI and the ADS/IDAC implementation at UMD. The studies may dovetail onto other planned studies being carried out in conjunction with the Light Water Reactor Sustainability Project. It is common practice in research studies such as those conducted in research simulators at Halden Reactor Project's Halden Man-Machine Laboratory (HAMMLAB) to conduct dual-purpose studies, for which multiple hypotheses are explored in a single study session. This ensures the cost effectiveness of the studies, given the limitied availability and high cost of using licensed control room operators from the nuclear industry.

4. CONCLUSIONS

There is a unique opportunity to take advantage of the interests and experience of the UI, OSU, INL, and UMD to carry out collaborative research that has the potential to fundamentally change the way data are gathered to inform HRA. The incorporation of significant new data sources as well as the potential for increased data feeds to HRA methods offers the potential to take HRA from the current use of static models with limited empirical basis to dynamic models based on sound psychological research and with an explicit empirical foundation. Such research also provides the possibility of substantially enhancing the safety of plants in the longer term.

This paper has outlined plans to improve HRA through the incorporation of a solid psychological foundation and simulator studies. The benchmark of data sources will allow a more realistic consideration of the factors that influence operator performance, empirically derived findings, dynamic modeling of operator actions, and reduction of uncertainty surrounding HRA estimates. Of course, the proposed combination of simulator studies and simulation is neither all-encompassing nor panacean. It does, however, provide the opportunity to focus on increasing and improving the data basis of HRA.

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Dedication

We dedicate this work to our dear friend and collaborator, Dr. Dana L. Kelly, who passed away unexpectedly during the early stages of this research. Dr. Kelly was a champion of HRA and the need to establish a more robust technical basis for the field. Much of this research to be carried out was made possible only because of Dr. Kelly's tireless pursuit of research funding to advance HRA. We are saddened that he will not be able to work with us to see his vision come to fruition.

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