Developing Methodology for Experimentation Using a Nuclear Power Plant Simulator

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1 Introduction

Many of today's most complicated systems are human-machine systems that involve extensive advanced technology and a team of highly trained operators. As these human-machine systems are so complex, it is important to understand the factors that influence operator performance, operator state (e.g., overloaded, underload, stress) and the types of errors that operators make. Thus, it is desirable to develop an experimental methodology for studying complex systems that involve team operations. This paper looks at Nuclear Power Plant (NPP) operations as a test case for building this methodology. The methodology will reference some aspects/details specific to NPPs, but the general principles are intended to extend to any complex system that involves team operations.

Nuclear Power Plant Operations

NPPs are composed of complex systems that are controlled via a Human System Interface (HSI) located in the Main Control Room (MCR). A minimum of three operators are required to manage and maintain a single nuclear reactor. Two individuals serve as Reactor Operators (RO) and the third is the Senior Reactor Operator (SRO). The types of tasks performed by operators have been classified differently over the years. O'Hara and his colleagues (2008; 2010) spent much time observing the roles of the operators in a NPP and suggest four categories of tasks: Monitoring and Detection, Situational Assessment, Response Planning, and Response Implementation. Monitoring requires checking the plant to determine whether it is functioning properly by verifying parameters indicated on the control panels (Figure 1), observing the readings displayed on screens, and obtaining verbal reports from other personnel. Detection occurs when the operator recognizes that the state of the plant has changed. Situational assessment tasks consist of evaluating current states of NPP systems to determine whether they are within required parameters. Response planning tasks consist of deciding on a plan to diagnose and perform appropriate actions when an event occurs. In NPPs, response planning is largely guided by standardized procedures. The procedures used during accident scenarios, and utilized in the present project, are symptom-based procedures called Emergency Operating Procedures (EOPs). Response implementation tasks consist of performing actions required by response planning (i.e. as directed by the EOP).

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Response implementation might include selecting a control, performing an action on the control, and watching responses of the system and process resulting from the action.

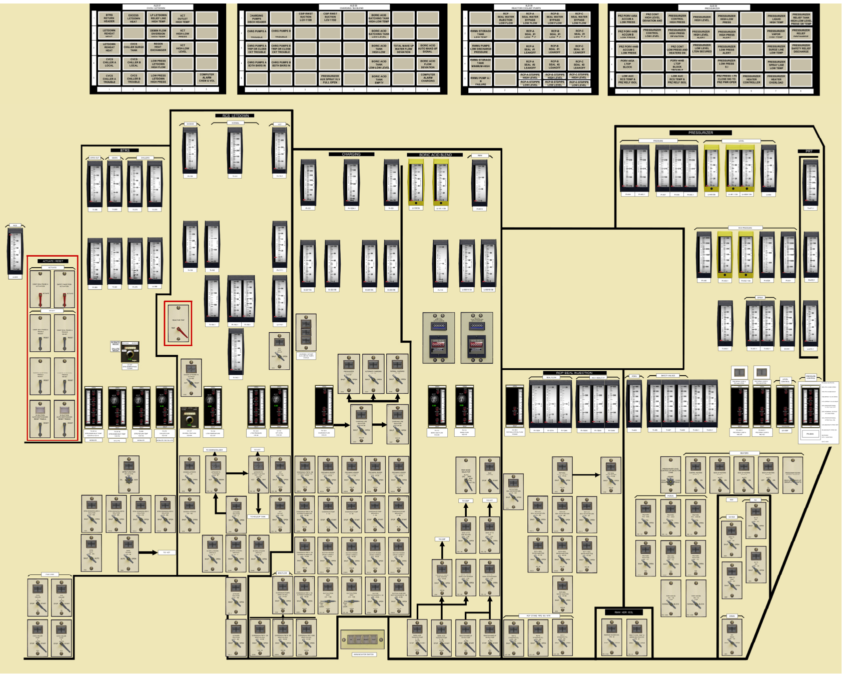


Fig. 1. An example of a NPP MCR control panel

2 Developing a Methodology

Work has been done in the NPP domain to understand the types of tasks operators perform, but systematically investigating and measuring operator performance, errors, and states in a highly controlled experimental setting while executing those tasks has been limited. Developing an appropriate experimental methodology is necessary to effectively evaluate questions concerned with the factors that influence operators' performance, errors, and states.

Test Case

A GSE Westinghouse Four-Loop Pressurized Water Reactor (PWR) simulator will be used in this test case. A non-operator population will serve as participants enabling a larger sample size and reduced cost for experimentation. As the term novice implies, this population has little to no experience with or knowledge of NPPs. Therefore, the environment needs to be simplified, in such a way that will induce participants to experience both the complexity and cognitive requirements incurred by trained operators. In other words, the methodological approach proposed in the present paper adheres to the principal of different but equal; the populations, EOPs, and control panels are different, but they are different in such a way that is controlled and induces the same level of task demand that would be experienced by each population.

The long-term objective for this work is to examine challenges related to the impact of technology upgrades, automation of tasks, and digital interfaces on the human operators. However, in order to answer those questions, the first step is to begin with exploring the effect that task type has on the workload within each operator role. That is the context within which the below methodology was developed.

Choosing the operating sequence

To reiterate, EOPs are the procedures that operators follow when certain symptoms are present in the plant. These procedures prescribe the type and order of actions that the operating crew takes. For example, if the plant automatically shuts down, operators would enter a procedure called E-0 that would lead them through actions that will diagnose the cause of the shutdown and provide the necessary actions to return the plant to a known safe state. In other domains, where procedures may not be used or not used in the same regimented way, the equivalent may be the event or scenario participants will face (e.g., a hurricane in disaster planning domain). The equivalent is whatever dictates the actions taken by participants. In this case, as the EOP chosen will literally dictate our participants' actions, we are equating EOP with scenario.

Four criteria were established for selecting EOPs best suited for a non-operator sample.

1. Select an EOP that best resembles the typical task flow that operators most commonly face.

A subject matter expert (SME) identified a limited number of frequently used EOPs. A task analysis is being conducted based upon the SME mapping for side-by-side comparison across EOPs. From this mapping, we, along with a SME in NPP operations, will attempt to discern characteristics of a typical task flow. The reason for this criterion is to preserve the fidelity of the task environment by maintaining the typical task flow experienced in a real NPP. Primarily, we want to avoid scenarios that include atypical tasks or order of events as it makes the results less generalizable to other scenarios.

2. Select an EOP that allows the investigation of all roles on the team.

The reason for this criterion was to allow for the assessment of phenomena as relevant to the ROs and the SRO separately, as their primary responsibilities are different. During an EOP, the SRO guides the ROs through symptom-based procedures to identify the events or causes of system alarms, while the ROs interact with control panels to perform actions to alter the state of the NPP. We are interested in understanding the workload associated with different tasks within each role on the team.

3. Select an EOP that requires participants to perform an equal or known ratio of the task types being investigated (e.g., monitoring and detection, and response implementation).

The reason behind this criterion was to enable experimental control of task complexity, which allows for direct comparison between task types. For example, if each operator receives 5 min of monitoring and detection tasking and 5 min of response implementation tasking with each type of tasking followed by administration of the NASA-TLX, then analyses will concretely inform the type of NPP tasks that are more demanding. These results may provide insight into the level of demand to expect when an EOP requires more of one type of task versus another.

4. Select an EOP that incorporates usage of all major categories of instrumentation and controls (e.g., light box, gauge, and switch) within the MCR.

The reason for this is to improve generalizability of experimental results to tasks beyond those carried out in the specific study.

Simplifying the operating environment

In addition to identifying criteria for EOP selection, several steps need to be taken to simplify EOPs and control panels for use with a non-operator sample. The first step is equating the total number of instruments on each panel to provide greater experimental control (Figure 2). This enables us to ensure that performance is not impacted by disparate visual complexity between operators, but, rather the experimental manipulations are the primary factors impacting performance.

Fig. 2a. Original control panel used by operators

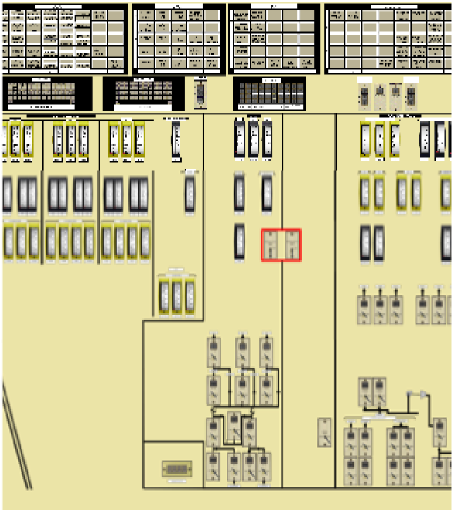
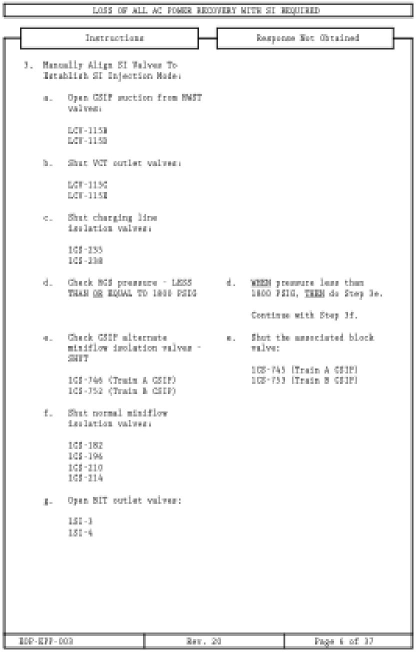


Fig. 2b. Simplified control panel for novice participants

The second step is to modify the EOPs (Figure 3), which refer to gauges and switches by an alphanumeric code, a name, or both, to refer to them only by their alphanumeric code. In addition, all gauges and switches with an alphanumeric code greater than seven characters have been re-coded to a code of seven or less characters, thus yielding a standardized naming convention that maintains the short-term memory principal of seven plus or minus two items. These changes enable simplified communication regarding control board elements. This is important because names of control panel elements are second nature to experts and therefore, are not primary factors that influence operators' performance.



LOSS OF ALL AC POWER RECOVERY WITH SI REQUIRED

Instructions	Response Not Obtained
3. Manually Align SI Valves To Establish SI Injection Mode:	
a. Open CSIP suction from RWST valves: LCV-115B LCV-115D	
b. Shut VCT outlet valves: LCV-115C LCV-115E	
c. Shut charging line isolation valves: 1CS-235 1CS-238	
d. Check RCS pressure - LESS THAN OR EQUAL TO 1800 PSIG	d. WHEN pressure less than 1800 PSIG, THEN do Step 3e. Continue with Step 3f.
e. Check CSIP alternate miniflow isolation valves - SHUT 1CS-746 (Train A CSIP) 1CS-752 (Train B CSIP)	e. Shut the associated block valve: 1CS-745 (Train A CSIP) 1CS-753 (Train B CSIP)
f. Shut normal miniflow isolation valves: 1CS-182 1CS-196 1CS-210 1CS-214	
g. Open BIT outlet valves: 1SI-3 1SI-4	

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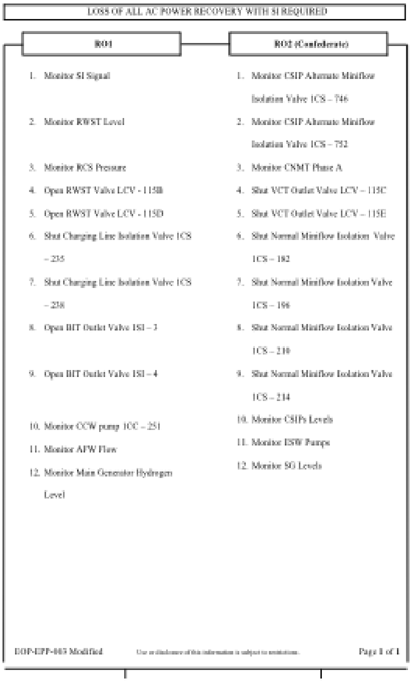
Fig. 3a. Portion of original EOP used by operators



LOSS OF ALL AC POWER RECOVERY WITH SI REQUIRED

RO1	RO2 (Confederate)
1. Monitor SI Signal	1. Monitor CSIP Alternate Miniflow Isolation Valve 1CS – 746
2. Monitor RWST Level	2. Monitor CSIP Alternate Miniflow Isolation Valve 1CS – 752
3. Monitor RCS Pressure	3. Monitor CNMT Phase A
4. Open RWST Valve LCV - 115B	4. Shut VCT Outlet Valve LCV – 115C
5. Open RWST Valve LCV - 115D	5. Shut VCT Outlet Valve LCV – 115E
6. Shut Charging Line Isolation Valve 1CS – 235	6. Shut Normal Miniflow Isolation Valve 1CS – 182
7. Shut Charging Line Isolation Valve 1CS – 238	7. Shut Normal Miniflow Isolation Valve 1CS – 196
8. Open BIT Outlet Valve 1SI – 3	8. Shut Normal Miniflow Isolation Valve 1CS – 210
9. Open BIT Outlet Valve 1SI – 4	9. Shut Normal Miniflow Isolation Valve 1CS – 214
10. Monitor CCW pump 1CC – 251	10. Monitor CSIPs Levels
11. Monitor AFW Flow	11. Monitor ESW Pumps
12. Monitor Main Generator Hydrogen Level	12. Monitor SG Levels

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Fig. 3b. Modified EOP used by novice participants

Locating control board elements also requires simplification. When an SRO directs an RO to implement an action using a specific control board element, the SRO will specify the panel element location and in the general region. For example, an SRO might state, "open valve X located on panel A1 in the lower right quadrant." This allows participants to easily locate elements thus reducing the impact that "locating" related issues will have on performance. Once again, as real operators are very familiar with panels, locating elements, generally, does not influence workload or performance.

Finally, real operators complete EOPs that contains tens of steps and will continue operations until the plant returns to a safe and steady-state, the novice participants will complete a fraction of these steps with a defined stopping point. Task type is maintained the amount of steps is reduced, we have kept task types the same. In addition, we wanted to make the duration of work similar to what might be experienced by operators. Although many training sessions can have scenarios that can last up to 3 hours, according to an operations SME, it is not uncommon to see 30-45 minute scenarios especially in initial licensing training. Thus, we thought this a reasonable and realistic starting point for scenario length. Obviously, due to extensive training and frequent practice, experts are able to perform actions more efficiently and effectively and, thus, can do more in less time. We kept have a realism associated with both the type of tasks and duration of work in this study in an attempt to induce similar levels of taskload experienced by operators.

We feel the criteria and simplifications described above, although tailored to the NPP domain, can be used as a starting point for developing experimental methodology for studying complex systems with team operations in other domains.

Selecting Measures

The final stage in the process of developing methodology is selecting measures that allow us to understand performance, determine error types, and understand the state of operators (stressed, overloaded, alert, etc.) while interfacing with complex systems. Performance can be measured in terms of response time, accuracy of actions, and detection of changes. Errors can be categorized along dimensions of slips, lapses, violations, and mistakes. In the NPP context, workload measurement is likely to be important for understanding performance and errors. This assumption is based upon the distinctiveness of the four primary tasks performed by operators. It may be that workload will vary with task type. However, assessing mental workload changes, in this context, may be challenging. No workload measure exists that has been validated in an NPP setting and many subjective assessments interrupt the task or are post-hoc. Interrupting the task changes the overall flow of events and perhaps even the demand requirements of the operators. Questionnaire administration in the middle of a scenario might either hinder operator performance and increase error when the task is resumed or the opposite could occur because a “break” allows the operator to reflect on the scenario event thus far. In comparison, a post-hoc measure might not be sensitive to the dynamic changes occurring in the NPP. The use of physiological metrics assist in circumventing these challenges.

There are many benefits to using physiological metrics as an assessment of mental workload. Most importantly, physiological metrics provide objective and continuous monitoring of the participant’s cognitive and physical state (Reinerman-Jones, Cosenzo, & Nicholson, 2010). Several physiological measures are being considered for inclusion in our NPP test case. Electroencephalography (EEG) measures neural activity and is sensitive to changes in mental workload (Figure 4). EEG allows for the continuous monitoring of brain activity without interfering with the primary task (Brookings, Wilson, & Swain, 1996).

Transcranial Doppler (TCD) sonography monitors cerebral blood flow velocity (CBFV) in intracranial arteries and has been commonly used in vigilance studies showing a decrease in CBFV paralleled by decreased performance for sustained attention of highly demanding tasks (Reinerman-Jones, Matthews, Langheim, & Warm, 2010). Vigilance is the detection of infrequent signals amidst non-signals or noise. Much of the operators’ responsibility fits the criteria of a vigilance task. Functional Near Infra-Red (fNIR) imaging monitors hemodynamic changes in oxygenated hemoglobin and deoxygenated hemoglobin in the prefrontal cortex (Ayaz et al., 2011).

Fig. 4. An ABM x10 EEG/ECG system worn by a participant

A study by Ayaz et al. (2010) showed that blood oxygenation increases are associated with increasing task difficulty. Electrocardiography (ECG) measures cardiac activity. Heart rate, heart rate variability, and inter-beat interval have been associated with mental workload (Jorna, 1993; Kramer, 1991; Roscoe, 1992, 1993; Veltman & Gaillard, 1996; Wilson, Fullenkamp, & Davis, 1994). Eye tracking measures ocular behavior and can provide insight into task difficulty by providing scan and fixation patterns (Reinerman-Jones, Cosenzo, & Nicholson, 2010).

Awareness of the many possible measures of performance, errors, and states along with understanding the scope and limitations of the operating environment (i.e. simulator capabilities/limitations, physical space, the modified EOPs, required team interaction, and the required actions) enables selecting appropriate assessments.

3 Conclusions

The methodology presented in this paper can serve as a foundation for future human factors testing in the NPP domain and other domains that involve complex systems and team operations. This work will expand understanding of performance in complex systems operations and explain factors, such as new technology or concepts of operation, impact on performance.

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