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Light Water Reactor Sustainability Program

Baseline Study Methodology for Future Phases of Research on Nuclear Power Plant Control Room Technologies

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Baseline Study Methodology for Future Phases of Research on Nuclear Power Plant Control Room Technologies

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ABSTRACT

In order to provide a basis for industry adoption of advanced technologies, the Control Room Upgrades Benefits Research Project under the Advanced Instrumentation, Information, and Control Pathway of the LWRS Program will investigate the benefits of including advanced technologies as part of control room modernization This report describes the background, methodology, and research plan for the first in a series of full-scale studies to test the effects of advanced technology in NPP control rooms. This study will test the effect of Advanced Overview Displays in the partner Utility's control room simulator

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ACRONYMS

CST	Condensate Storage Tank
DOE	Department of Energy
HSSL	Human system Simulation Laboratory
IFE	Institute for Energy Technology
INL	Idaho National Laboratory
LWRS	Light Water Reactor Sustainability
NPP	Nuclear Power Plant
OPAS	Operator Performance Assessment System
OVD	Overview Display
RCP	Reactor Coolant Pump
US	United States

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1. Introduction

This research is a part of the United States (U.S.) Department of Energy sponsored Light Water Reactor Sustainability (LWRS) Program conducted at Idaho National Laboratory (INL). The LWRS Program is performed in close collaboration with industry research and development programs, and provides the technical foundations for licensing and managing the long term, safe, and economical operation of current nuclear power plants (NPPs). One of the primary missions of the LWRS Program is to help the U.S. nuclear industry adopt new technologies and engineering solutions that facilitate continued safe operation of NPPs and extension of current operating licenses.

One cornerstone of sustaining the existing fleet of light water reactors s is control room modernization. The Electric Power Research Institute (Fink et al. 2004) describes several potential drivers of control room modernization, which include:

- Addressing obsolescence and lack of spare parts
- Meeting the need for equipment replacement due to high maintenance cost or lack of vendor support for existing equipment
- Implementing new functionality necessary to add beneficial capabilities
- Improving NPP performance, human system interface functionality, and NPP reliability
- Enhancing operator performance and reliability
- Addressing difficulties in finding young professionals with education and experience with older analog technology.

Although all of the modernization drivers listed above are recognized as potential reasons for modernization, the reality is that obsolescence and lack of vendor support for aging systems have been primary drivers for many control room modernization efforts. In response to obsolescence issues, NPPs typically embark on system-by-system upgrades leaving the control room largely analog with disparate digital systems intermixed throughout. While this approach may meet the needs of addressing obsolescence, it will not necessarily result in an end-state that fully exploits modern technologies to support the most efficient operator performance or enhance plant performance. These like-for-like replacements may limit the use of advanced functionality in favor of reducing the perceived technical and regulatory risks involved in such projects.

Modern technology affords the opportunity to visualize information in more intuitive ways, distill a large amount of information to operators in an understandable manner, and provide decision support and automatic aids. These improvements are being incorporated into many newer technologies such as overview displays (OVD), advanced alarm systems, computer-based procedures, and NPP automation technologies. Although some of these technologies are currently available, they are not being widely adopted by the nuclear industry.

In order to provide a basis for industry adoption of advanced technologies, the Control Room Upgrades Benefits Research Project under the Advanced Instrumentation, Information, and Control Pathway of the LWRS Program will investigate the benefits of including advanced technologies as part of control room modernization (Le Blanc et al, 2015a, Le Blanc et al., 2015b,). The specific goals of this research are to:

1. Identify an ideal control room modernization end state

    a. Identify advanced control room technologies that provide quantifiable benefits
    b. Identify features of those technologies that are most useful
2. Facilitate the transition to an ideal modernization end state
    a. Provide evidence for use of key technologies in NPP's business case for modernization
    b. Connect research results with meaningful measures of NPP performance (e.g., key performance indicators) and safety.

Ideally the modernization end state is a fully integrated control room with modern technologies and consistent interfaces for the operators to interact with. This approach is hypothesized to enhance plant performance, operator performance, and efficiency compared to an existing analog control room or a hybrid control room. However most plants are not likely to embark on a full-scale modernization at one time, therefore a more realistic approach to arriving at a modernized control room is a phased approach with specific system upgrades occurring during each 18-month outage cycle. It is hypothesized that an upgraded hybrid control room with targeted advanced technologies will enhance plant performance, operator performance, and efficiency compared to an existing analog control room. The degree to which control room technologies enhance performance will depend on many factors including how well-integrated the new technologies are into the existing control room (for hybrid control rooms), what functionality is provided by the technology, and the degree to which adverse effects of technologies (such as increased interface management workload) are addressed in the design of the human system interface. The purpose of this approach is guide the phased adoption of these technologies by providing an empirical basis for the effect they have on operator performance in the control room.

Although it is assumed that a fully modernized and integrated control room with consistent design and consistent human system interfaces for all upgraded systems will support operator performance better than piecemeal upgrades that were driven solely by obsolescence management, at this time there is little to no quantitative data that could be used as the basis for plants and utilities to justify a full-scale modernization. In the research described in this report, control room technologies (including interfaces for specific systems and candidate technologies that might augment system upgrades) will be systematically tested in a series of experiments. These experiments will provide a quantitative basis for characterizing the benefits of the control room technologies on operator performance and efficiency. This work will assess, characterize, and quantify the benefits of control room upgrades in various stages of modernizations. This research will be conducted in close collaboration with a partner utility undergoing a large-scale modernization effort.

Each technology or interface that is considered as part of the partner utility's end-state vision will be experimentally evaluated in full-scale simulator studies using a combination of objective quantitative performance measures and qualitative input on the design. This research will be conducted in several phases, aligning with each phase of modernization at the partner utility.

In addition to providing a basis for selecting and implementing advanced technology in NPP control rooms, this research is designed to meet many challenges associated with determining the effect of new technologies in full-scale simulator studies. Full-scale simulator studies are complex, with a large number of variables contributing to overall crew and plant performance. Further, limitations in the number of crews available for full-scale studies make it difficult to run full-scale studies with enough statistical power to identify the influence of technologies on crew performance. Detecting differences due to specific control room technologies has been difficult in previous work, limiting the nuclear industry's overall understanding of the impact of new technology on plant performance. This study will seek converging evidence from several full-scale simulator studies along with smaller, more controlled micro-scale experimental tasks to explore the effect of the new technologies. The full-scale studies will provide high ecological validity, but due to the complexity may have small to moderate effect sizes. The smaller studies may have less ecological validity, but with the greater degree of control and the reduced complexity of the environment, it is more likely that moderate to large effects sizes will be evident. The full scale simulator studies will be carried out in a methodologically rigorous manner that will maximize the ability of the studies to provide generalizable, quantitative results about the overall effect of the technologies on performance as described in Section 3.

The microscale tasks will provide detailed timing and accuracy data related to each interface. Taken together, the results of these studies should provide sufficiently strong evidence of the impact that these new technologies have on performance.

This report describes the background, methodology, and research plan for the first in a series of full-scale studies to test the effects of advanced technology in NPP control rooms. This study will test the effect of advanced Overview Displays (OVDs) in the partner utility's control room simulator. The report is organized as follows.

- **Overview Displays**. This describes the rationale for selecting OVDs as the first technology to be tested, and the benefits to operators expected from implementation. This section also describes the specific OVDs that are developed for this research and the specific benefits expected form those displays.
- **General Methodological Approach**. This describes the general methodology and the rationale for the approach including benefits and challenges of conducting full-scale simulator studies, the rationale for selecting the number of crews and scenarios to test, and the general approach to performance measures selected for these studies.
- **Methodology for Baseline Study.** This describes the methodology for the baseline study including scenarios, performance measures and experimental protocol.
- **Summary and Conclusions.**

2. Overview Displays

The technology selected for the first study is OVDs. OVDs were selected for several reasons including:

1. The partner utility is interested in implementing OVDs as part of their control room upgrades.
2. OVDs can be designed to be information only displays that support monitoring and particular tasks but do not replace existing systems, meaning there may be fewer risks and regulatory barriers to deploying them than fully replacing a plant system.
3. The display design principles employed in OVDs can be translated to other displays in the control room. Understanding the features and impact of OVDs, in general, will also provide valuable input to the design of system OVDs that might go into the specific system upgrades the partner utility has planned.

These factors make the OVDs an ideal target for a carefully controlled experimental study that researchers can use to refine quantitative methodology and provide insights into the effect and benefits of control room technologies

2.1 General Background on OVDs

It has been proposed that OVDs can improve nuclear operator's overall performance and situation awareness. OVDs may also decrease operators' mental and physical workload. Despite the numerous studies conducted on OVDs, there is little no empirical evidence that demonstrates statistically significant effects on operator performance, making it difficult to assess whether the performance improvement claims of OVDs will be realized in an operational context. One goal of this research is to address this gap and provide objective quantifiable evidence of the effect of OVDs on operator performance.

OVDs have been developed for many industries, such as process control and oil and gas, but much of the research on the effectiveness of OVDs has been done in the nuclear industry. Across research literature, there is not a single definition of OVDs, but designers and researchers tend to agree on many of the overall purposes and functions of OVDs. Group view displays and general OVDs are two common types of OVDs developed for nuclear operating rooms. The main difference between the two is that group view displays are much larger in comparison to regular OVDs. Group view displays are meant to be seen by all crew members at any given time during a scenario whereas regular OVDs are more diverse; they can be viewed by an entire crew or only be seen by a specific member. General OVDs can vary in size, but are typically smaller than group view displays.

The Nuclear Regulatory Commission (NRC Library, NUREG-0700 Rev. 2) states that OVDs are used for the following purposes;

- Providing an overview
- indicating plant status
- flexibility in searching information
- support for rapid shift of view
- overall assessment at a glance
- relevant to the viewer's context
- mimic format
- Display of safety parameters and functions

Most OVDs are designed to summarize a plant's most important indicators and offer a synopsis of the plant in a display that is in a centralized position. This is intended to help operators determine a summary of the entire plant by referring to a single screen instead of having to manually walk and scan the entire operating room.

Another proposed strength of OVDs is that they should help the operators obtain an overall view of the plant status, become aware of major changes in the plant status, and identify minor changes in the plant state that are important to the plant condition. This is accomplished through regular OVDs as well as group view displays. Both of these displays are meant to aid operators in identifying ongoing operations and help them to respond to plant deviations.

According to the NRC (NRC Library, NUREG-0700 Rev. 2), an OVD should support operators in rapidly shifting their focus of attention when tracking an evolving event. While operators have a tendency to focus on their specific responsibilities on a particular issue, an OVD should direct attention to all responsibilities of new conditions. It should also support operators in alternating their focus between their own responsibilities as well as the entire status of the plant in a manner that does not disrupt continuous evaluations.

Another proposed strength is the feature of providing overall assessment at a glance. In a traditional nuclear power plant control room, operators must walk the entire room and look at all sorts of indications to gain an overall assessment of the plant. With OVDs, operators can obtain an overall evaluation at a glance. In order for operators to do this, the OVDs must ensure that the information contained in an OVD is presented in a manner where the description of the situation of the plant can be recognized at a glance. The NRC provides specific guidance on how this can be accomplished.

An OVD should be abstracted to a level that is consistent with the operators' information requirements for determining plant status. This is because an OVD is intended to aid operators in monitoring and assessing changes in the plant state. Information that is selected should be consistent with the types of decisions operators must make when monitoring the plant (such as the determination of challenges to plant safety).

Another typical feature of OVDs is that of mimic format: there are partial mimics located on OVDs as well as full system mimics. Mimics overall are intended to provide a high-level indication of plant status. They may provide a useful framework for organizing plant information to support the operators in locating specific information. They are also intended to help operators determine flow path of various functions. An important strength of mimic format displays is the feature of being able to detect system faults at a faster rate (Weigmann,, Essenberg, Overbye, & Rich, 2002).

Researchers of OVDs have proposed that operators' overall performance is improved by OVDs within two main factors; time and efficiency. For example, when OVDs are absent, operators generally follow procedures and conduct analysis of the plant by walking and evaluating the entire nuclear operating room. This takes quite a bit of time. The proposal of OVDs is limiting this time and increasing efficiency of the analysis of the plant and completion of the procedures by glancing at the OVDs and obtaining all the necessary information without having to walk and evaluate each individual process throughout the entire operating room. The overall conclusion of this proposal is to help operators determine more about a plant's status in a fraction of the time which allows them to make quicker decisions and get through various procedures at an earlier rate to become more efficient in regards to time.

A proposed strength of OVDs is that they improve situation awareness. This strength stems from the process of having a summary of the plant's status in one central location. On a regular day or when the OVDs are absent, nuclear operators' situation awareness is usually catered to a specific task set aside in a procedure they are inclined to follow. Their awareness is also limited to role-specific responsibilities. When OVDs are present, it is proposed that all operators can become aware of the many pieces of information regarding the plant that they would normally pay little attention to due to a lack of time or due to their specific responsibilities. OVDs may help make operators aware of all of the important information (not just role specific information) in a fraction of the time. This is expected to improve situation awareness for the individual operators as well as for the crew as a whole.

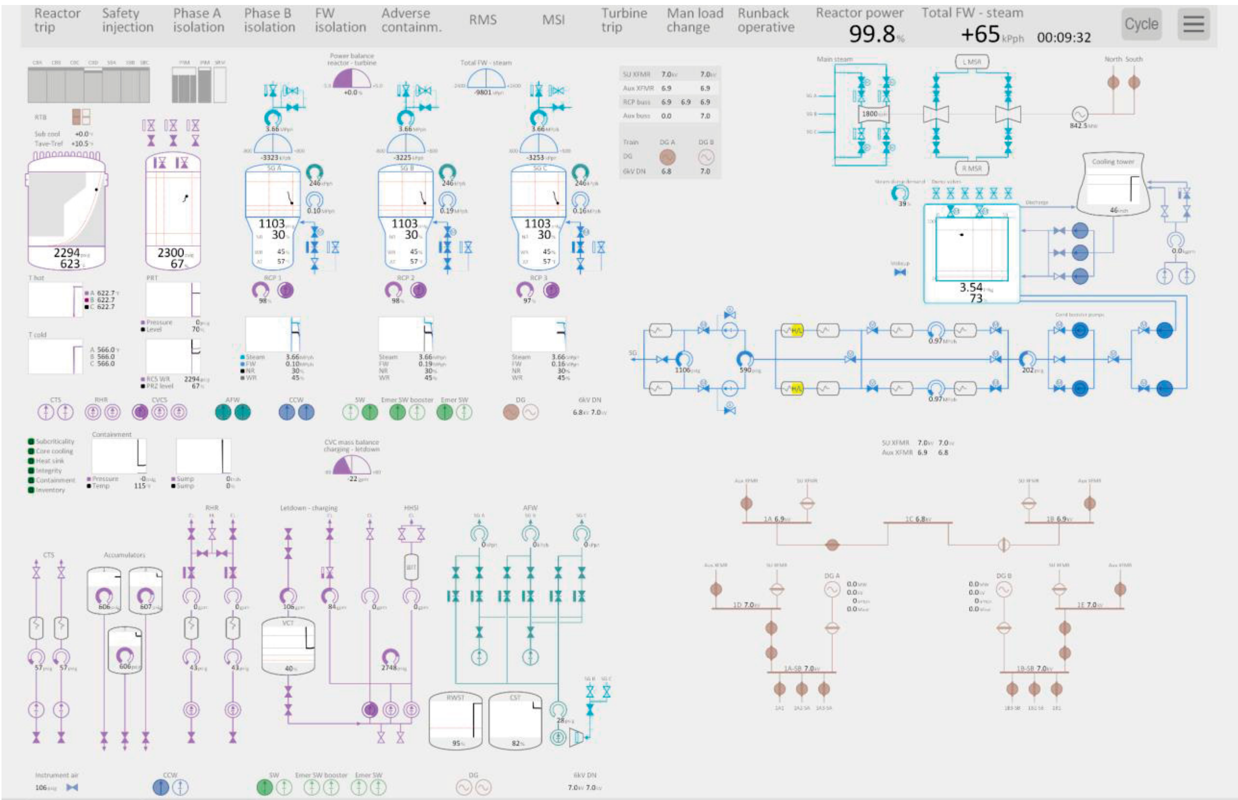
A final proposed strength of OVDs relates to a reduction of physical and mental workload of nuclear operators. Researchers have indicated this is a result from a change of the normal process of procedures. For example, the normal process of a procedure causes the operators to walk the entire control room and pay attention to numerous indications which can cause mental/physical workload. Additionally traditional analog control panels often require the operator to make mental calculations and comparisons in order to determine the meaning or impact of the indications they read. OVDs can help operators by presenting the information in context and not requiring mental interpretation of the information. It is expected that this decrease in effort will also reduce overall workload for the operators

2.2 OVDs tested in this study

INL and the Institute for Energy Technology (IFE) have collaboratively developed OVDs for a nuclear power plant control room. These displays are designed to provide an overview of plant status under normal, abnormal, and emergency operating conditions to the entire crew. The displays are intended to support monitoring of normal conditions as well as monitoring during emergency conditions. The displays are not intended to replace existing displays in a control room, but are instead designed to enhance and distill the information on the control boards. Many of the graphical elements are designed to make it easier to see status by showing relationships between important parameters and providing additional contextual details such as trends, set points, and ranges of many values (See Figure 1). This

OVD design will be adapted to represent the partner utility's plant systems and will be connected to plant simulator data in the training simulator.

Figure 1. OVD design that will be tested in the baseline study.



The specific features of the OVDs are:

1. All information needed for monitoring is provided in one place providing:
   - At-a-glance status determination of plant conditions
   - Continuously monitored critical safety function status trees
   - Display of all equipment status for important equipment
   - Display of trends of important parameters
2. Trend displays make it easier to see changes over time. Auto scaling on trends allows for detection of small or large changes depending on the conditions. This is a useful feature because it provides a more reliable trend on a measured scale versus the area of the scale having to grow to display the full trend. A possible weakness that has been noted due to auto scaling trends is the aspect of a way to determine whether or not the trend has auto scaled (this is difficult because the trend lines just look like regular trend lines whether they are auto scaled or not). In order to compensate for this feature, the OVDs provide an indication that shows how the trend has been auto scaled.
3. Mass/Balance displays make it easy to see an imbalance due to a leak. There are semi-circle indicators with a line down the middle. The line represents the balance between the in-flow and

the out-flow of water (or steam). If the line moves from its original set point, it provides an immediate perceptual indication that there is a leak.

4. Multiple parameters on a single graphical display, which also provide information about trip set points (and distance of current trends from set points). The contextual information provided in these displays makes it easier to determine the impact of the development of these parameters.

Section 3.2.5 describes how these specific features will be tested in the experimental study.

3. Method

This section describes the general methodological approach to this research and the specific methods that are utilized in the baseline study.

3.1 General Methodology

This section describes the rationale for the number of crews selected for the experiment, and the number of scenarios selected for each crew. This section also describes the general approach to performance measurement.

3.1.1 Number of Crews

A main objective of this research is to be able to make a rigorous assertion that adoption of some particular technology (or group of technologies) will result in tangible benefits to plants that adopt it. In order to make this claim, several things must be done:

1. We need to decide what type of benefit we are looking for, and find ways to quantify it
2. We need to be able to distinguish the effect of a new technology from other effects that may be present including:
    a. Learning effects
        i. from seeing same or similar scenarios repeatedly
        ii. from being exposed to new technology
    b. Variations in difficulty among scenarios
    c. Crew effects
        iii. overall better or worse performance than other crews
        iv. different operating styles / attitudes to the new technology
3. If multiple technologies are tested, we must be able to tell which technology (or interaction of technologies) to attribute the observed effects.

Item 1 is addressed analytically by reviewing literature on the candidate technologies (see section 2 for an example for OVDs), by reviewing operational experience with the candidate technologies, and by careful consideration of appropriate performance measures once identifying the hypothesized benefits.

In general, we achieve items 2 and 3 by bringing several crews into the simulator, and presenting each crew with several scenarios in each of several simulator configurations. In expanding from a pilot study to a full-scale study, we must decide how to allocate the additional resources: creating additional simulator configurations; creating additional scenarios and running more scenarios per crew; and bringing in additional crews.

3.1.1.1 Learning effects

In an ideal world, one would test a new technology with a paired experiment: each crew is presented with each task twice, with and without the new technology. In the real world, this is sometimes achievable for routine micro tasks, but presenting a rare accident sequence twice in a row mostly measures how much more familiar the event is the second time around.

One approach to this problem is to accept the harm done by repeating a scenario exactly. One can randomize whether each scenario is presented with or without the new technology first, and present a great many scenarios. The theory is that if we compare "first time without technology, second time with technology" against "first time with technology, second time without", in both cases performance will be better the second time, but by a larger margin in the former case.

In this approach, the technology effect becomes a second-order effect, and even in cases where performance is easy to measure on an interval scale, it can easily require many hundreds of trials to detect an effect. If performance is measured on an ordinal scale, it may be impossible.

A further practical difficulty in the HSSL is that it is undesirable to repeatedly present and take away the extra technology on a scenario-by-scenario basis. We prefer to thoroughly familiarize a crew with a technology configuration, then present several scenarios in the same technology configuration. This avoids a second kind of learning effect: crews will perform better with familiar technology than unfamiliar technology, and we hope to minimize the difference in how well they utilize the available technology by training them to proficiency before starting to collect data.

This same argument also limits the number of configurations it is reasonable to present to a single crew: each configuration change imposes an additional training and practicing burden on the schedule.

3.1.1.2 Variability Among Scenarios

Another approach to mitigating scenario-related learning effects is to design several scenarios that are of similar difficulty, but not identical, and create "pairs" of comparable scenarios. This avoids the worst of the scenario-specific learning effects.

The effectiveness of this technique relies on how well designed the scenario pairs are. If the scenario designer achieves perfect balance, one can in principle attribute better performance in one half of a pair to the type of technology used. It is not reasonable to expect such perfect balance, however. A sensible precaution is to randomize the order in which each pair is presented, so that any imbalance is in favor of the technology half the time and against it half the time.

A desire to avoid repeating identical or nearly-identical scenarios places an upper limit on the number of scenarios that can reasonably be run with the same crew.

3.1.1.3 Crew Effects

Each crew has a different experience level and a different operating style. Even if two crews are similar on paper -- same years of experience, trained on the same procedures by the same trainer -- there will still be differences in how efficiently each crew member works, differences in management style between different crew supervisors, differences in how cohesive each team is. In the pilot study conducted in FY15 for this project, and many other studies, these differences among crews are often far larger than any effect due to scenario difficulty or type of technology in use.
The fact that these differences exist is the single biggest reason why studies aim to present the same crew with pairs of similar scenarios. Determining if the same crew is better or worse when one condition is change with a small to moderate number of crews, is much more effective at eliciting signals of interest than a large number of comparisons between crews is.

However, in order to demonstrate a plant will benefit from adopting a new technology, it is necessary to show that most crews will benefit from the new technology. Showing that one or two, or even four, crews all benefitted from use of a given technology is not a proof that other crews will feel the same way. Because there is variation among crews, it is necessary to expose a representative cross-section of the available crews to the new technology, and show that significantly more of them benefitted from the new technology (performed better while using it, or were less stressed or frustrated while using it, or reported preferring the new technology in a debrief) than were harmed by it.

The exact number of crews necessary to show that significantly more of them benefitted than were harmed will vary with the type of data being collected and with how the crews are selected. In the simplest model of the situation -- each crew is randomly selected, and asked to give the new technology a thumbs-up or a thumbs-down -- it is necessary to have all 5 of 5, or at least 7 out of 8, or at least 12 out of 16, crews report favorably on the technology before one can conclude with 95% confidence that more than half of crews believe the new technology is an improvement.

3.1.1.4 Multiple Technologies

If n different technologies are being tested, they can be deployed in 2n different combinations. It is not practical to subject the same crew to more than a few different technology configurations and then train them to proficiency on those configurations. Even with 2 new technologies, presenting all 4 configurations to the same crew would likely be a two-week effort in the HSSL. Presenting the same crew with more than 2 configurations raises a further question of whether to try to assemble larger sets of comparable scenarios, or settle for deploying the scenarios in pairs but having few head-to-head comparisons between some of the possible configurations. Creating sets of 4 scenarios of comparable difficulty is a very hard task for the designer, and each group of 4 can be presented in 24 different orders.

It is desirable to limit the complexity of the experimental design by minimizing how many different subgroups of events need to be randomized, and to limit the difficulty of the analysis by maximizing the number of easily interpretable head-to-head comparisons.

3.1.1.5 A Minimal Design for Testing 2 Technologies

The benefits project originally proposed to test the impact both of OVDs and advanced alarms. This means that 4 technology configurations would need to be tested: the basic configuration; only OVDs added; only advanced alarms added; and both new technologies added. Controlling for the learning effects described above requires that each pair be presented in both orders.

Accordingly, the smallest experimental design that achieves all the goals mentioned above uses 8 crews (see Table 1).

Table 1. A balanced design for testing two technologies.

Crew number:	First configuration:	Second configuration:
1	Alarms off, displays off	Alarms off, displays on
2	Alarms off, displays on	Alarms off, displays off
3	Alarms off, displays off	Alarms on, displays off
4	Alarms on, displays off	Alarms off, displays off
5	Alarms on, displays off	Alarms on, displays on
6	Alarms on, displays on	Alarms on, displays off
7	Alarms off, displays on	Alarms on, displays on
8	Alarms on, displays on	Alarms off, displays on

Note each of the four configurations appears four times each in this table, and each head-to-head comparison of configurations happens twice (and in a different order the second time.)
Additional crews would make it possible to better control for imperfect scenario design, and better constrain the effects of the various technologies.

Note that giving up the ability to consider the interaction of the two new technologies -- testing only three configurations rather than all four – would not enable one to do all of the above with six crews rather than eight. The eight crews above provide four "with and without OVDs" and four "with and without advanced alarms" direct comparisons.

3.1.1.6 Summary

There are benefits both to increasing the number of crews and to increasing the number of scenarios per crew. But there is a point of diminishing returns to increasing one but not the other.

There are limits to how many sufficiently-different scenarios can be created. In the pilot study conducted in FY2015, increasing the number of scenarios from four to six was a challenge. For the type of scenarios used in the pilot, somewhere between eight and twelve scenarios per crew is probably the maximum that will ever be feasible.

Testing two different technologies at once, and distinguishing how much benefit is due to each technology, cannot reasonably be done with fewer than eight crews.

An important goal of the project is to be able to generalize from this small study and make recommendations about what technologies a plant should adopt and have all of their crews use. Demonstrating that a majority of crews will benefit from a technology requires the use of a significant sample of crews. Making statistically rigorous claims about 'the typical crew' is impossible with fewer than 5 crews and still very difficult even with 8.

In conclusion, to test a single technology in a way that allows for detecting difference due to technologies and separating them from all the learning effects, crew effects, and scenario effects, an absolute minimum of four crews need to be tested in a minimum of four scenarios per crew (and two per technology configurations). In order to achieve results that are generalizable to other crews a minimum of eight crews need to be tested.

3.1.2 Performance Measures

This section describes the general approach to measuring performance in the full scale simulator studies. The same methods will also be applied in the micro tasks where applicable.

- **Simulator Logs.** The simulator automatically logs actions (e.g., freeze, run, injection of faults and malfunctions, actions taken on the plant by the operator, and actions taken from the instructor station) and can be configured to log any plant parameters that are of interest in the scenario. The relevant plant parameters are based on the scenario and procedures (e.g., if the procedure requires operators to keep steam generator level within a particular control band, steam generator level would be an appropriate parameter to log and use for operator performance).
- **Structured Observation.** The researcher will use a modified version of Operator Performance Assessment System (OPAS) to observe crew performance (Skraanning, 2004). OPAS uses predefined actions and sequences (determined by the scenarios and procedures used) to objectively define crew performance. The research team has developed a modified tool that captures scenario events such as injected malfunctions, alarms, and other parameter set points as well as capturing operator events such as detecting alarms, diagnosing a fault and carrying out specific actions. See Figure 2 for an example of the modified OPAS tool.

Figure 2. Example of modified OPAS tool.

- **Eye tracking.** Each crew member will be outfitted with mobile eye tracking glasses for the full-scale simulator study and micro tasks. Figure 3 shows the use of the eye tracking glasses and Figure 4 shows data visualizations that can be developed using eye tracking.

Figure 3. Example use of eye tracking glasses in control room simulator.

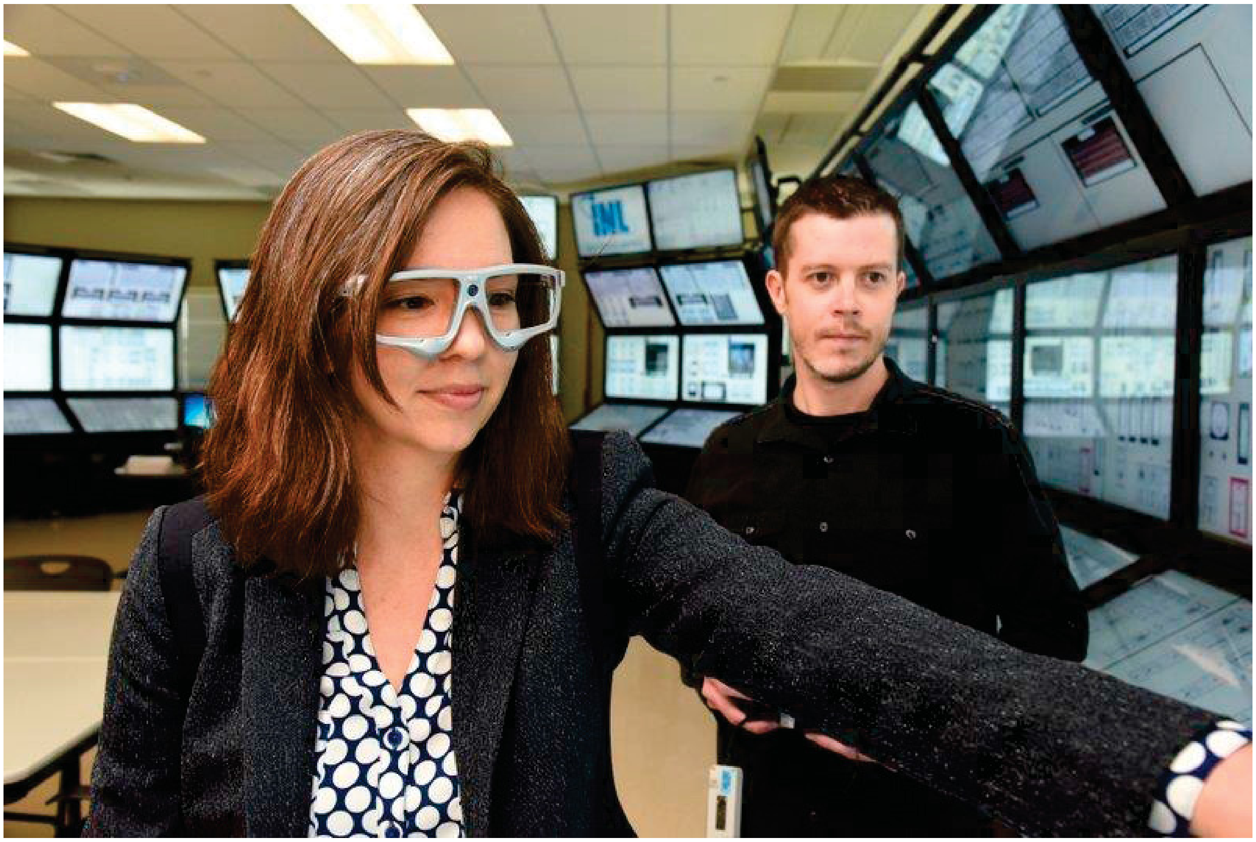
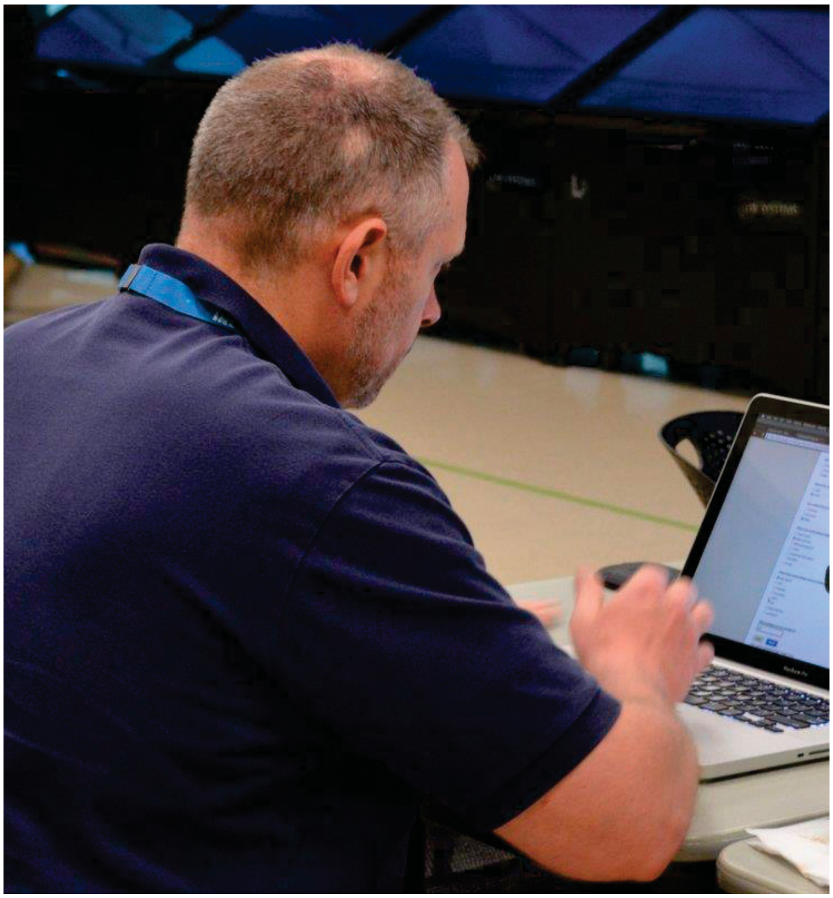


Figure 4. Data visualization from eye tracking glasses.

- **Wearable physiological device.** Each crew member will be outfitted with a wearable device that records heart rate, steps taken (pedometer), and blood pressure.
- **Freeze-Probe Questionnaire.** At predefined points in each scenario, the simulation will freeze, and crews will respond to a brief questionnaire to assess situation awareness and workload. Figure 5 shows an operator responding to a freeze probe questionnaire.

Figure 5. Operator responding to freeze probe questionnaire.



- **Post-Scenario Questionnaire.** Following each scenario, each crew member will respond to a questionnaire that assesses workload, situation awareness, usability of technology, and perceived performance.

3.2 Experiment 1 Full-Scale Study

The objective of this study is to investigate the effect of OVDs developed by IFE on crew performance, workload, and situation awareness.

3.2.1 Hypothesis

Compared to without OVDs, scenarios conducted with OVDs will have:

- Reduced operator error
- Enhanced plant performance

- Reduced crew workload
- Increased ability to operate with broader safety margins
- Increased crew situation awareness (individual and team)
- Enhanced ability to detect off normal conditions
- Increased efficiency
- Increased operator satisfaction

3.2.2 Participants

The participants will be eight crews of three operators from the partner utility. The three operators in each crew will serve the roles of control room supervisor and two reactor operators in the experimental scenarios.

3.2.3 Apparatus

The IFE OVDs will be adapted to partner utility's systems and connected to their training simulator. Displays will be temporarily placed in the training simulator for experimental testing, and removed afterword.

3.2.4 Design

The independent variable will be manipulated within crews.

1. With OVDs
2. Without (baseline)

The dependent variables will be assessed with the measurement techniques described in Section 3.1.2. The following list describes how each hypothesized effect will be assessed. Detailed descriptions of performance measures can be found in Le Blanc et al., 2015a:

- Reduced operator error
    - Assessed via modified OPAS tool
- Enhanced plant performance
    - Deviation in plant parameters (via simulator logs)
- Reduced crew workload
    - Blink rate and blink duration (continuously monitored via eye tracking)
    - Heart rate variability and other physiological measures (via wearable device, these measure are still under development)
    - NASA TLX, assessed during freeze probe and at end of scenario
- Increased ability to operate with broader safety margins
    - Simulator logs of safety-related parameters, per tech specs
- Increased crew situation awareness (individual and team)
    - Individual fixation to importance ratio (measured for critical time periods via eye tracking)
    - Individual freeze probe questionnaire (modified SACRI)
    - Aggregate crew scores on the above two measures
    - Crew Situation questionnaire (under development)
- Enhanced ability to detect off normal conditions
    - Time to detect off-normal conditions (via OPAS)

    - Eye tracking
  - Increased Efficiency
    - Scenario completion times (overall)
    - Time to diagnose (via OPAS)
  - Increased operator satisfaction
    - Post-scenario questionnaire
    - In addition the research team will use eye tracking to assess qualitative measures such as use of OVDs (fixation time across the entire scenario).

3.2.5 Scenario Design

We designed two matched sets of two scenarios for the full-scale experiments. The scenarios are intended to be directly comparable, but different enough to avoid a strong learning effect that might be present if repeating an identical scenario. The scenarios will be moderately complex and will utilize normal, abnormal, and emergency operating procedures. The general formula for designing the scenarios is presented in an approximate scenario timeline below:

1. Baseline/steady state situation (~3-4 minutes)
2. Instrument failure or minor equipment malfunction (5-15 minutes)
3. Major fault that takes the operator into AOPs, and eventually EOPs (first indication ~16 minutes, evolving through ~35 minutes)
4. Diagnoses and begin recovery (~35- minutes)
5. Scenarios will be designed to be ~45 minutes long and will terminate once a few mitigation actions have been taken

The scenarios are designed such that experienced crews will be somewhat challenged by them (thus performance will vary enough to detect differences based on the presence of technology), but not so difficult that the crews will be overwhelmed and abandon or misuse the technologies we are testing. The scenarios are designed to utilize and evaluate the features of the OVDs described above. The scenarios contain as many of the elements in Table 2 as possible.

Table 2. Summary of OVD features, resulting scenario design requirements, and performance measure implications.

Feature of OVDs	Scenario Design Requirements	Performance Measure Requirements
All information needed for high level monitoring is provided in one place	The scenarios need to have periods in which high level monitoring can be assessed. Additionally, testing the ability to monitor from a single location should be built into the scenario (e.g. , standard post-trip actions can be done with OVDs, or provide an opportunity to challenge a critical safety function)	• One or more of the freeze probes should be timed to capture assessment of plant status via OVDs • Efficiency and accuracy of conducting tasks such as standard post trip actions should be assessed
Trend displays make it easier to see changes over time	Changes in plant parameters that develop gradually and have an effect on procedure path or diagnosis.	• Capture detection of changes in plant parameters observationally or by operator actions that are dependent on those changes
Mass/Balance displays make it easy to see an imbalance due to a leak.	The scenarios should include a leak that could be detected on the mass/balance displays, but would require mental calculation without them	• Capture mass/balance displays as an area of interest in eye tracking to determine if it was used to detect leak and measure in coordination with time-to-detect leak
Multiple parameters on a single graphical display	Part of the scenarios should require operator to understand plant parameters in the context of other variables and with respect to trip set points	• Capture parameter displays as areas of interest in eye tracking to determine if it was used to measure off-normal conditions in coordination with time-to-detect conditions/ initiate procedure

3.2.5.1 Scenarios

The full scenarios can be found in appendix A, and are summarized below.

- Scenario 1. Faulted steam generator and steam generator tube rupture. A steam leak upstream of main stream isolation valves (un-isolable), the crew should respond to the increase in steam flow as well as the cooling down of the reactor coolant system (RCS) (lowering pressurizer level and pressure).

- Scenario 2. Condensate Storage tank (CST) rupture and high vibration on reactor coolant pump (RCP). During night shift normal operations, pre outage work in progress in the area of scaffolding is dropped and has damaged the piping from the CST and water is spraying. The leak is not isolable due to the amount of water coming from the leak. Five minutes after the leak is reported a vibration alarm on RCP 2B will annunciate and the vibration will build in over five minutes to require a trip of the RCP. Scenario 3
- Scenario 3. Large break loss of coolant accident (LOCA). A leak from the RCS in containment will be ramped in over a 20 minute period starting from a small leak to a RCS leak of 30%.
- Scenario 4. Steam generator tube rupture. The initiating event will be Main Feed Water pump B trip causing a reactor cutback. Five minutes into the AOP a steam generator tube rupture of 40% will be ramped in over the next 15 minutes. (The goal is for the crews to identify the RCS leak first by the lowering pressure and PZR level, as well as determine a leak into the SGB based on the differential flows on the mass balance indicators. All found on the OD).

3.2.6 Order and counterbalancing

The order of conditions (with and without technologies) and scenarios will be carefully counterbalanced (see example in section 3.1.1.5, Table 1) so that the effects of different crews and technology configuration can be separated.

3.3 Experiment 2 Micro Tasks

The purpose of this experiment is to gather quantitative data on accuracy and efficiency of reading information on the OVD compared to traditional display panels. This experiment will consist of micro-scale tasks to investigate the use of OVDs compared to the traditional analog control panels.

3.3.1 Hypothesis

Compared to the traditional displays, The OVDs will facilitate:

- More efficient search for information
- Faster response times
- More accurate responses

3.3.2 Design

The independent variable is presentation style (analog panel versus OVD). The dependent variables are:

- Time to first fixation (via eye tracking)
- Search efficiency (via eye tracking)
- Response times
- Response accuracy

3.3.3 Apparatus

The IFE OVDs and relevant portions of the analog control panel will be presented to each operator depending on the condition. The IFE OVDs will be presented in the Partner utility's training simulator in the same manner as the full scale experimental studies.

3.3.4 Task

The operator will be asked to respond to a set of questions for each display type. The full list of questions can be found in Appendix B, and some example questions re shown below.

4. Summary and Conclusions

This report describes the rationale and methodology for a general approach to testing the effect of new technologies in NPP control rooms. The approach described balances the need for rigor required to understand the separate effects of each technology, for separating learning, crew and scenario effects form technology effects, and the need for realistic environments and scenarios to test the effect of new technologies in the nuclear. The study will be carried out in FY 2017.

5. References

Fink, R., D. Hill, and J. O'Hara, 2004, *Human Factors Guidance for Control Room and Digital Human-System Interface Design and Modification: Guidelines for Planning, Specification, Design, Licensing, Implementation, Training, Operation and Maintenance*. EPRI, Palo Alto, CA, the U.S. Department of Energy, Washington, DC: 2004, 1008122.

Le Blanc, K, Powers, D., Joe, J., Spielman, Z., Rice, B., and Fitzgerald,, K.., 2015a . A Pilot Study Investigating the Effects of Advanced Nuclear Power Plant Control Room Technologies: Methods and Qualitative Results. No. INL/EXT--15-36432. Idaho National Laboratory (INL), Idaho Falls, ID (United States), 2015.

Le Blanc, K., J. Joe, B. Rice, T. Ulrich, and R. Boring, 2015b, *Benefits of Advanced Control Room Technologies: Phase One Upgrades to the HSSL, Research Plan, and Performance* Measures, INL/EXT-15-35381, Idaho National Laboratory.

NRC Library, NUREG-0700 Rev. 2

Roth, E. M., Lin, L., Thomas, V. N., Kerch, S., Kenney, S. J., & Sugibayashi, N. (1998). Supporting Situation Awareness of Individuals and Teams Using Group View Displays. *Proceedings of Human Factors and Ergonomics Society, 42*: 244-248.

Sebok, A. (2000). Team Performance in Process Control: Influences of Interface Design and Staffing Levels. *Ergonomics, 43*:8, 1210-1236, DOI: 10.1080/00140130050084950

Skraaning, G., 2004, Experimental Control Versus Realism: Methodological Solutions for Simulator Studies in Complex Operating Environments, HWR-361, Halden Reactor Project, Halden, Norway

Weigmann, D. A., Essenberg, G. R., Overbye, T. J., & Rich, A. M. (2002). Motion in Mimic Displays: Effects on the Detection and Diagnosis of Electrical Power System Failures. Human Factors and Ergonomics Society.

Appendix A

Scenario Descriptions

Scenario 1

	Item Name	Item Description
1.	**Name**	*Faulted SG with SG Tube Rupture*
2.	**Scenario #**	1
3.	**Expected Run Time**	45 min to 1 hr
5.	**Scenario Description**	*A steam leak upstream of MISV UV-170 (un-isolable), the crew should respond to the increase in steam flow as well as the cooling down of the RCS (lowering pressurizer level and pressure). (the overview displays OD) should help the crew identify the faulted SG by identifying the increased steam flow on SG1 and the balance indicators)*
6.	**Simulator Details**	*Normal*
7.	**Procedures Required**	*Reactor Trip, 9EO01 Standard Post Trip Actions, Section 4.0 Diagnostic Action, 9EO05 Excessive Steam Demand, Attachment 113*
8.	**System(s)**	*Overview Displays*
9.	**Personnel Roles Involved**	*Senior Reactor Operator (SRO)* *Reactor Operator (RO)* *Balance of Plant Operator (BOP)*
10.	**Task Location(s)**	*Main Control Room*
11.	**Start State**	*Reactor Power 100% normal at power conditions.*
12.	**Initiating Cues to the Operator**	*Steam leak upstream of MISV UV-170 (un-isolable), Reactor Trip*
13.	**Indicators**	*Trends on overview displays indication of a leak, Reactor Trip Alarm*
14.	**Execution/Performance requirements**	*The crew should trip the reactor and enter 9EO01- Standard Post Trip Actions.* *The crew should step through the procedure and enter Section 4.0 Diagnostic Action.* *The crew should identify the excessive steam flow and enter 9EO05 Excessive Steam Demand* *When the faulted SG1 reaches 200 PSIA a SGTR of 25% should be initiated* *The crew should identify SG1 as the most affected SG (This can be done using the OD by verifying the pressure difference between the SGs as well as trends)* *The crew should use Attachment 113 to Isolate SG1* *The crew should identify that SG1 is not drying out and should re-diagnose the event to include a SGTR.*

15.	**Diagnosis Required**	*Recognition of steam leak, recognition of reactor trip*
16.	**Timing**	*N/A*
17.	**Potential Errors**	*Lack of diagnosis for leak and reactor trip*
18.	**Recovery Opportunities if Omitted**	*If reactor does not automatically trip, operator can do this manually*
19.	**Terminating Indications**	*Depending on the time of re-diagnoses the scenario can be stopped upon the transition to 9EO04 SGTR*
21.	**Operating Experience**	*Basic nuclear operating control room experience and simulator experience*

Scenario 2

	Item Name	Item Description
1.	**Name**	*CST Rupture and High Vibration on RCP2B*
2.	**Scenario #**	2
3.	**Expected Run Time**	45 min to 1 hr
5.	**Scenario Description**	*Pre outage work in progress in the area of CTA-HV-1 and 4, scaffolding is dropped and has damaged the piping from the CST and water is spraying on both CTA-HV-1 and 4 causing them to short out and lose power. The leak is not isolable due to the amount of water coming from the leak.*
6.	**Simulator Details**	*Normal*
7.	**Procedures Required**	*AOP-XXX, 9EO01 Standard Post Trip Actions, Section 4.0 Diagnostic Action, 9EO02 Reactor Trip, Attachment 42 Aligning Essential Aux Feed Water Pumps to the RMWT*
8.	**System(s)**	*CTA-HV-1 & 4, Overview Displays*
9.	**Personnel Roles Involved**	*Senior Reactor Operator (SRO)* *Reactor Operator (RO)* *Balance of Plant Operator (BOP)*
10.	**Task Location(s)**	*Main Control Room*
11.	**Start State**	*Rx 100% power Night shift normal operations*
12.	**Initiating Cues to the Operator**	*CST Leak and Reactor Trip*
13.	**Indicators**	*Trends of overview displays indication of a leak, Loss of Power, Reactor Trip Alarm*
14.	**Execution/Performance requirements**	*The crew will enter AOPXXX due to a lowering CST level.* *The crew will respond to the high RCP vibration and trip the reactor and then the RCP and enter 9EO01 Standard Post Trip Actions* *Upon Reactor trip inadvertent MSIS occurs closing all MSIV.* *The crew should trip the reactor and enter 9EO01- Standard Post Trip Actions. (Many of the post trip indications are located on the OD and will support improved performance on identifying value and trend)* *The crew should step through the procedure and enter Section 4.0 Diagnostic Action.* *The crew should determine that all Acceptance Criteria has been met at enter 9EO02 Reactor Trip* *The crew should continue working to resolve the CST issue using the AOP and send out Attachment 42 Aligning Essential Aux Feed Water Pumps to the RMWT*
15.	**Diagnosis Required**	*Recognition of leak and reactor trip*
16.	**Timing**	*Five minutes after the leak is reported a vibration alarm on RCP 2B will annunciate and the vibration will build in over five minutes to require a trip of the RCP. AOPXXX*

17.	**Potential Errors**	*Lack of diagnosis for leak and reactor trip*
18.	**Recovery Opportunities if Omitted**	*If reactor does not automatically trip, operator can do this manually*
19.	**Terminating Indications**	*Scenario can be stopped once the field operator has completed the alignment of the EAFWP suction to the RMST.*
21.	**Operating Experience**	*Basic nuclear operating control room experience and simulator experience*

Scenario 3

	Item Name	Item Description
1.	**Name**	*Large Break LOCA*
2.	**Scenario #**	3
3.	**Expected Run Time**	*45 min to 1 hr*
5.	**Scenario Description**	*The crew will identify the loss of flow in one of the RCS loops on a single transmitter. This will either cause a reactor trip or if not cause an alarm. The crew will then perform AOP XXX. The crew will shortly receive containment radiation alarms and a lowering pressurizer pressure and level. The crew should identify an RCS leak and trip the reactor and possible initiate SIAS. The purpose of this scenario is to allow the Operators to use the OD for a majority of their component and lineup verification as well as checking flows and pressures*
6.	**Simulator Details**	*Normal*
7.	**Procedures Required**	*AOP-XXX, 9EO01-Standard Post Trip Actions, Section 4.0 Diagnostic Action, 9EO03 Loss of Coolant Accident*
8.	**System(s)**	*Flow Transmitter Failure, Containment Radiation Alarm, Reactor Trip, Overview Displays*
9.	**Personnel Roles Involved**	*Senior Reactor Operator (SRO)* *Reactor Operator (RO)* *Balance of Plant Operator (BOP)*
10.	**Task Location(s)**	*Main Control Room*
11.	**Start State**	*Reactor Power 100% normal at power conditions.*
12.	**Initiating Cues to the Operator**	*Initiating event is a flow transmitter failure on one of the RCP loops followed shortly by a containment radiation alarm.*
13.	**Indicators**	*Containment Radiation Alarm, Reactor Trip Alarm*
14.	**Execution/Performance requirements**	*The crew should trip the reactor and enter 9EO01- Standard Post Trip Actions.* *The crew should step through the procedure and enter Section 4.0 Diagnostic Action.* *The crew should determine the need to enter 9EO03 Loss of Coolant Accident*
15.	**Diagnosis Required**	*Recognition of flow transmitter failure, recognition of a leak from the RCS in containment, recognition of a lowering pressurizer pressure and level*
16.	**Timing**	*A leak from the RCS in containment will be ramped in over a 20 minute period starting from a small leak to a RCS leak of 30%*
17	**Potential Errors**	*A lack of diagnosis for reactor trip*

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18.	**Recovery Opportunities if Omitted**	*If reactor does not automatically trip, operator can do this manually*
19.	**Terminating Indications**	*The crew should determine the need to enter 9EO03 Loss of Coolant Accident and reach step 57 of the procedure*
21.	**Operating Experience**	*Basic nuclear operating control room experience and simulator experience*

Scenario 4

	Item Name	Item Description
1.	**Name**	*Steam Generator Tube Rupture*
2.	**Scenario #**	4
3.	**Expected Run Time**	45 min to 1 hr
5.	**Scenario Description**	*The initiating event will be Main Feed Water pump B trip causing a reactor cutback. The crew will enter 40AO-9ZZ09 and perform the actions of the loss of the feed pump. The goal is for the crews to identify the RCS leak first by the lowering pressure and PZR level, as well as determine a leak into the SGB based on the differential flows on the mass balance indicators. All found on the OD*
6.	**Simulator Details**	*Normal*
7.	**Procedures Required**	*40AO-9ZZ09, 9EO01-Standard Post Trip Actions, Section 4.0 Diagnostic Action, 9EO04 Steam Generator Tube Rupture*
8.	**System(s)**	*Overview Displays*
9.	**Personnel Roles Involved**	*Senior Reactor Operator (SRO)* *Reactor Operator (RO)* *Balance of Plant Operator (BOP)*
10.	**Task Location(s)**	*Main Control Room*
11.	**Start State**	*Reactor Power 100% normal at power conditions.*
12.	**Initiating Cues to the Operator**	*Reactor Trip Alarm, Main Feed Water Pump B Trip*
13.	**Indicators**	*Loss of feed pump B, Reactor Trip, Initiating of a SIAS*
14.	**Execution/Performance requirements**	*The crew should identify a lowering Pressurizer pressure and level and manually trip the reactor as well as manually initiate a SIAS.* *The crew should trip the reactor and enter 9EO01- Standard Post Trip Actions. (Many of the post trip indications are located on the OD and will support improved performance on identifying value and trend)* *The crew should step through the procedure and enter Section 4.0 Diagnostic Action.* *The crew should identify in Section 4.0 a possible SGTR and proceed to 9EO04 Steam Generator Tube Rupture.*
15.	**Diagnosis Required**	*Recognition of Main Feed Water Pump B Trip, Recognition of Reactor Trip, Recognition of Steam Generator Tube Rupture*
16.	**Timing**	*Five minutes into the AOP a SGTR of 40% will be ramped in over the next 15 minutes.*
17.	**Potential Errors**	*Lack of diagnosis of main feed water pump B trip, and reactor trip*
18.	**Recovery Opportunities**	*If reactor does not automatically trip, operator can do this manually*

	if Omitted	
19.	**Terminating Indications**	*Crew reaches step 33 in the procedure.*
21.	**Operating Experience**	*Basic nuclear operating control room experience and simulator experience*

Appendix B

Micro task Questions

RCS Display

A.) Are all four RCPs running?
B.) What is RCS Pressure?
C.) What is the status of the letdown system?
D.) Should the RCPs be tripped?
E.) Should SIAS be in?
F.) Is the RCS 24˚F or more subcooled?
G.) What is Pressurizer Pressure?
H.) Is Tc 560 - 570˚F?
I.) Is SG pressure 1140 – 1200 psia?
J.) How many charging pumps are running?

ECCS Display

A.) What is Containment pressure?
B.) Is Containment pressure less than 2.5 psig?
C.) How many Containment Spray pumps are running?
D.) What is the flow rate of LPSI pump B?
E.) What is the total Essential AFW flow?
F.) What is the level in the CST?
G.) Is the level in the RWT greater than 73%
H.) What is the HPSI flow to 2A Tc?
I.) What is the discharge pressure of HPSI pump A?
J.) What is the spray flow from the A Containment Spray pump?

Turbine Display

A.) What is the status of both Heater Drain pumps?
B.) Does vacuum exist in the Main Condenser?
C.) What is the speed of Main Feedwater pump A?
D.) What is the discharge pressure of the Condensate pumps?
E.) What is the status of the high pressure turbine stop valves?
F.) Are both Main Generator output breakers open?
G.) How many CW pumps are running?
H.) What is the Main Generator output?
I.) What is the discharge pressure of Main Feedwater pump B?
J.) How many Steam Bypass valves are open?

Electrical Display

A.) What is the status of buss NAN-S01?
B.) How many kilovolts are indicated on buss PBB-S04?
C.) What is the status of DG B?
D.) How many MW does DG A have?
E.) What is the status of PKC-M42?
F.) Where is the power coming from supplying PBA-S03?
G.) How many volts on PGA-L33?
H.) Which power supply is powering NAN-S05?
I.) What is the Mvar on DG B?
J.) How many amps on DG A?