ONTOLOGY TO GUIDE SCENARIO DESIGN TO EVALUATE NEW TECHNOLOGIES FOR CONTROL ROOM MODERNIZATION

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ABSTRACT

Modernization of nuclear power plants (NPPs) are introducing new human-system interface (HSI) technology that may have unanticipated impact on control room operations. Introduction of HSI thus requires careful evaluation and integrated system validation involving human-in-the-loop experiments with high-fidelity simulation and realistic scenarios. To support the technology evaluation in modernization of NPPs, this paper reports our research on constructing an 'scenario development ontology' for the nuclear industry. We conducted a literature review to produce a preliminary flow chart of the scenario development process and verified the flow chart through interviews with ten domain professionals. The interviews confirmed the key steps in the process flow chart and provided a compendium of approximately 100 scenario attributes, which were divided according to their relevance to HSI evaluation. The next step will be to conduct additional interviews to expand and generalize the ontology that can facilitate vendor and industry evaluation of current and future control room modernization projects. This ontology is particularly intended to facilitate vendor and industry evaluation of current and future control room modernization projects.

Keywords: Scenario design, instrumentation and control, control room modernization, technology evaluation, scenario ontology, integrated system validation

1. INTRODUCTION

Most nuclear power plants (NPPs) in the United States were designed and built at least 40 years ago. The control rooms of these plants consist of largely analog human-system interfaces (HSIs) that have become obsolete. The nuclear industry is under tremendous market pressures to become more reliable and cost-efficient. At the same time, the industry has strong regulatory pressures to maintain strict safety standards, including mandates to add new technology and processes. The combination of these factors are motivating the nuclear industry towards control room modernization [1, 2]. As the industry replaces obsolete analog HSI, and introduces new functionality, NPP control rooms are becoming hybrids with a combination of analog and digital components [3].

Many studies have indicated that the implementation of advanced technologies can introduce unanticipated effects on safety and performance [1, 3, 4], including software susceptibility to common mode failures, increased operator workload in transient conditions, and out-of-the-loop control room operator (CRO) performance. Further, there are concerns that hybrid HSI can bring new challenges to CROs as the monitoring strategies and cognitive processing of distributed analog HSI may be fundamentally different from those for all digital centrally located HSI. To safeguard against failure and to ensure reliable plant performance, integrated system validation (ISV) involving human-in-the-loop experiments with high-fidelity simulation and realistic scenarios are mandated by regulators. ISV can evaluate whether emerging technologies will support CROs' safe and efficient operation of NPPs.

Proper ISV or evaluation depends on the effectiveness of the scenarios in illuminating the benefits and vulnerabilities of these technologies. The U.S. Nuclear Regulatory Commission (NRC) has provided guidance on the development and selection of simulation scenarios, albeit primarily to support regulatory reviews [5-7]. However, both practitioners and researchers remain challenged by scenario design because the NRC guidelines are limited, prescribing only general scenario attributes (e.g., initial conditions, malfunctions, major transients) and do not address the full scope of simulation scenario uses. Scenarios containing different events can be designed to achieve similar objectives. Thus, the scenario development process is largely left to the creativity and judgment of subject matter experts (SMEs), all of whom have extensive operational experience, most have worked as CROs, and are integral to their NPP's simulation programs. Yet, few SMEs have formal training in relevant disciplines like human factors engineering or educational psychology. Further, the majority of scenarios developed by these local SMEs are for CRO training and evaluation rather than for ISV. Training-based scenarios prompt CROs to practice their procedural knowledge and skills in abnormal plant operation. Evaluation-driven scenarios are most often developed for CRO licensing and recertification. In the absence of detailed guidance, much of the scenario development process is based on local custom and needs. In the comparatively less common situation of simulations for new HSI evaluation and ISV, existing scenarios are typically modified for the purpose.

The ISV review guidance [5, 7] states that performance-based tests should be used to assess the hardware, software, and human elements of an integrated system's design, but it fails to address *how* scenarios should be developed or what scenario attributes that should be incorporated to most effectively assess specific technologies. The HSI for different NPP functions make different cognitive demands on CROs and their effective use (and potential failure modes) may require different monitoring and/or control strategies, especially when new digital HSI is being introduced in a largely analog control room. For example, computer-based procedures (CBPs) are automatic computerized procedures with functions, interfaces, benefits, and vulnerabilities different from those of advanced turbine or feedwater control systems. For CBPs, it would be important to evaluate whether the operator detects that the recommended procedure is no longer appropriate for the NPPs evolving condition, or that a malfunction that causes the CBP system to skip steps within a procedure. In contrast, for advanced turbine control, it would be important to test the CRO's ability to monitor the appropriateness of automation settings and to detect abnormal conditions under different operating situations. Thus, to evaluate CBPs and turbine control systems will likely require different scenario attributes to effectively reveal each technology's benefits and vulnerabilities.

In other industries such as healthcare, there is a large literature on the use of simulation for different purposes – operator training, operator assessment, new process refinement, technology evaluation, accident investigation – as well on how best to design scenarios for those applications [8-14]. A taxonomy to support evaluation of scenario development and delivery has recently been published [15]. We therefore sought to develop a 'scenario development ontology' for the nuclear industry that would support a similar range of uses and provide more formal scenario design guidance to scenario developers.

This ontology is particularly intended to facilitate vendor and industry evaluation of current and future control room modernization projects.

2. METHODS

We first conducted a literature review focused on the process of scenario design and development. A systematic search of the literature revealed 22 relevant articles, although these were largely in the healthcare domain. The review resulted in a preliminary flowchart of the scenario development process (**Figure 1**) and an interview guide to solicit feedback from SMEs who developed simulation scenarios for their local NPPs. We used the interview guide to conduct semi-structured interviews with ten SMEs. Example questions included were: "*What is your typical process for developing a scenario for training and/or evaluation?*" and "*What different types of scenarios exist? What makes them different?"* We also observed eight simulation scenarios at four different NPPs. Information from NUREG-0711 [7] and feedback from the first round of interviews were used to supplement the interview guide in preparation for the next round of interviews.

The interview data were collated and coded using grounded theory methodology [16-18]. Three researchers used an iterative process of interview transcript review and coding, discussions to reach consensus, recoding, and refinement of the interview guide to solicit clarifying information during subsequent interviews. The three researchers independently reviewed and coded each interview transcript, tagging all topics of potential relevance. During group discussions, they identified and reached consensus on individual scenario development process attributes, steps, goals, contingencies and measures, as well as hierarchical groupings, potential ordering, and all possible inter-dependencies. Uncertainties and disagreements were reformulated as questions and added to the interview guide. The hierarchical groups of attributes and goals were then mapped onto the related procedural steps of the scenario development as a flowchart to capture similarities, discrepancies, and missing information for follow up studies. **Table 4** presents the attributes for consideration during the scenario development process for HSI evaluation.

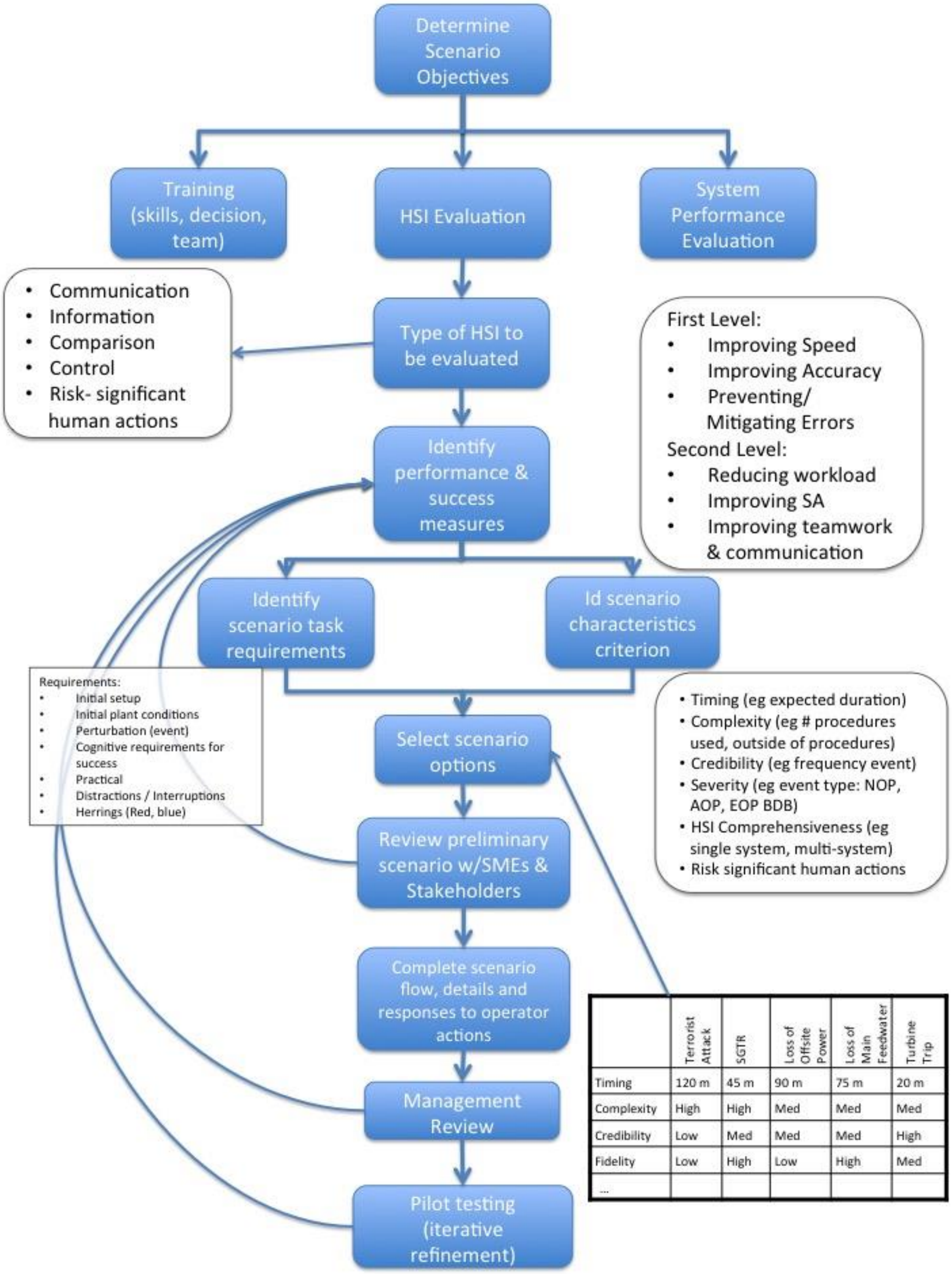
3. RESULTS

Figure 1 presents the first iteration of our scenario development process flowchart. The first step (**1** in **Figure 1**) of creating a scenario is to determine the objective of the scenario. In this first iteration, three possible purposes (i.e., **why**) for scenario development were considered: CRO training, HSI evaluation, and system performance evaluation. Since we were primarily interested in HSI evaluation, much of the remaining ontology development focused on this topic. Because different types of HSI differ in terms of their functional requirements, operator demands and potential operational benefits and weaknesses, the next step is to specify which type of HSI is being evaluated. This drives consideration, at a high level, of the types of CRO tasks and cognitive functions to be engaged and evaluated. The next step is to determine **how** performance on these tasks and functions will be evaluated. Performance metrics, typically targeting operator and system performance as surrogates, are the subject of a separate paper. Nonetheless, the goal here is to determine how one will know that the HSI design is acceptable and, if flaws are detected, to ascertain sufficiently the nature of those vulnerabilities so as to mitigate them.

The next step (**2a**) is to identify the specific task requirements that will be induced by the HSI. For example, for CBPs, operators must look at a computer screen, identify their 'place' in the procedural sequence, determine the data acquisition or control tasks expected, and indicate (i.e., click or type) the requested data or check-off of completion. Here, the scenario developer wants to consider the interactions between operator and HSI that are most likely to lead to safety critical task failures.

The next step (**2b**) is to identify the simulated event characteristics or attributes that will best support the scenario objectives while considering the tasks to be performed and measures to be assessed. **Table 1** provides a list of event attributes discerned from the literature and verified during our interviews and observations. At this step, the developer is considering different scenarios that will contain the essential event attributes while engaging the CROs in the desired tasks with the HSI. Most scenarios are variations of secondary malfunctions that lead to major accidents, some of which are specified by the NRC [6].

Figure 1. Initial Scenario Development Flowchart



	Terrorist Attack	SGTR	Loss of Offsite Power	Loss of Main Feedwater	Turbine Trip
Timing	120 m	45 m	90 m	75 m	20 m
Complexity	High	High	Med	Med	Med
Credibility	Low	Med	Med	Med	High
Fidelity	Low	High	Low	High	Med
...					

Table 1. Twelve Scenario Attributes Discerned from the Literature Review

Initial setup	Timing (e.g., expected duration)
Initial plant conditions	Complexity (e.g., no. of procedures used)
Perturbation (event)	Credibility (e.g., frequency of event)
Cognitive requirements for success	Severity (e.g., event type)
Practical distractions / interruptions	HSI Comprehensiveness (e.g., single system)
Herrings (red, blue)	Risk significant human actions

The next step (**3**) is to begin to design the scenario, codifying the event so as to meet the requirements defined in **Step 2**. At this '**what**' stage, the scenario developer iteratively specifies an increasingly level of detail of the scenario's evolution, considering the requirements and other contingencies of the prior stages. For this stage, our initial literature review identified five commonly used major transients and provides aspects of four event attributes – timing, complexity, credibility, and fidelity (**Table 2**).

Table 2. Detailed List of Major Transients from Initial Literature Review

Accident Description	**Terrorist Attack**	**SGTR**	**Loss of Offsite Power**	**Loss of Main Feedwater**	**Turbine Trip**
Timing	120 min	45 min	50 min	75 min	20 min
Complexity	High	High	Med	Med	Med
Credibility	Low	Med	Med	Med	High
Fidelity	Low	High	Low	High	Med

Analysis of the interview transcripts provided a compendium of approximately 100 scenario attributes, which were divided according to their relevance to HSI evaluation (**Table 4**). For HSI evaluation, the scenario attributes were organized under related steps of the scenario development process to augment the details discerned from the literature review (**Table 1**). **Table 3** provides the scenario attributes extracted from the interviews, complemented by our simulation observations.

The next step (**4**) is to have the scenario reviewed by SMEs and relevant stakeholders (e.g., NPP management, HSI vendor). In many NPPs, there are multiple levels of review and approval that must be integrated into the scenario development process, potentially at earlier or later Steps. The subsequently refined scenario would then be 'finalized' (**Step 5**) for pilot testing (**Step 6**) by mapping out the scenario flow and fleshing out all of the detailed simulator and simulation conditions necessary to run the scenario. **Step 5** requires mapping out the scenario's anticipated series of operator and plant responses, which include contingencies, distractions, and a success path. This "**What if**" step is critical to designing a scenario that will yield consistent results permitting aggregation of performance across operator teams. SME input, simulation instructor experience and brainstorming can be useful at this step to assure that the scenario addresses all conceivable operator responses to ongoing simulated events. Pilot testing (**6**) is absolutely crucial to validate technical assumptions (i.e., how the scenario will run) and expected operator behavior (e.g., unanticipated actions or inactions at various stages of the scenario), identify weaknesses or missing elements that degrade scenario reliability, and to assess whether the intended performance measures are likely to yield meaningful evaluation data for the targeted HSI (e.g., acceptable levels of sensitivity and specificity). It can be useful to present the results of these pilot tests to SMEs to gain insight into identified scenario shortcomings and unanticipated operator behaviors. As shown in **Figure 1**, the iterative nature of scenario development mandates feedback loops at various stages to further refine, and possibly change substantially, various aspects of the design.

Table 3. Scenario Attributes by Category

Results from Literature Review	Detailed Attributes Derived from SME Interviews	
Initial setup	Precursors to planned event, initial conditions and associated attributes	
Initial plant conditions	Initial plant conditions (typically but not always normal operations)	
Perturbation (event)	Initial trigger such as an instrument malfunction	
CRO cognitive requirements for success	Mitigation strategy Situation awareness Board awareness Systems thinking	Screen navigation Need for operator to input information Need to manipulate multiple variables Need to manipulate plant conditions
Practical distractions / interruptions	Other events (usually minor or unrelated) Extraneous personnel	Other task demands
Herrings (red, blue)	Absence/wrong indication of control element	
Timing (e.g., expected duration)	Scenario duration	Event timing (sequential vs. concurrent)
Complexity (e.g., no. of procedures used)	Procedure selection Multiple events Number of events per scenario Event timing (sequential vs. concurrent)	Coupling of subsystems Deviation from SOP Inability to deal with problem in usual way Unfamiliar/rare procedures or actions Removal of key display system Available mitigations
Credibility (e.g., frequency of event)	Based on real events Frequent failure modes	Logical flow Realism
Severity (e.g., event type)	Event evolution/rate of change Magnitude of event	Personal risk (radiation, etc.) Failed automation
HSI Comprehensiveness (e.g., single system, multi-system)	*Intentionally left blank (see Discussion)*	
Risk significant human actions	*Intentionally left blank (see Discussion)*	

Table 4. Scenario Attributes Organized in Relation to Process Steps for HSI Evaluation.

Step	Step Description	Associated Scenario Attributes	
1	Identify performance and success measures	Available mitigations Criteria for when to proceed to next scenario step Purpose/focus of scenario	Mitigation strategy Procedure selection Situation awareness Critical actions/tasks
2a	Identify task demands on operators	Board awareness Critical actions/tasks Systems integration/thinking Need for manual adjustments Need for operator to input information	Need to manipulate multiple variables Need to manipulate plant conditions Screen navigation
2b	Identify event attributes	Adjust scenario for operator experience Balanced workload for operators Based on real events Complexity Contingencies Deviation from SOP Event evolution/rate of change Event timing (sequential/concurrent) Flexibility Frequent failure modes Integrated plant response Logical flow Magnitude of event Multiple events	Nature of recovery Need to get to fundamentals Number of events per scenario Obstacles to success Personal risk (of radiation, fire, etc.) Procedural focus Realism Scenario duration Scenario objectives Success path Team dynamics Time pressure Types of scenarios
3	Select or create scenario events that meet requirements defined in step 2	Absence/wrong indication of control element Coupling of subsystems Data selection for display Delay/mask of obvious progression Deviation from SOP Failed automation Feedback from prior use of scenario Frequent failure modes Gaps in/loss of CBP Inability to deal with problem in usual way Incongruity between displays and real world	Legacy system failures Level of control (automatic) Missing information Modified/new hardware NRC list of scenarios/events NUREG-1021 Unfamiliar/rare procedures or actions Prior actual event reports Removal of key display system Role of alarms Unexpected system mode Wrong procedure selected by CBP
4	Review event selection with SMEs & stakeholders (e.g. PRA analysts)	Iterative review and refinement Multiple levels of review and approval	Pilot test Post development validation

Step	Step Description	Associated Scenario Attributes	
5	Select root causes or triggers for events	Event evolution/rate of change Initiating event	Instrument malfunction
6	Map out the scenario's anticipated series of operator and plant responses to events	Contingencies Critical tasks/actions Distraction Event evolution/rate of change Initial plant conditions Initiating event	Instrument malfunction Logical flow Multiple events Role of alarms Success path

4. DISCUSSION

First, we aimed to verify the six critical steps of the preliminary scenario development flowchart by mapping codes, i.e., scenario attributes, extracted from the interview data for relevant steps of the process (**Table A-1**). **Step 1** involves identification of performance and success measures. From the interview data, these may include mitigation strategies, procedure selection, and critical actions or tasks and thus are dependent on the purpose of the scenario. **Step 2a** requires identification of task demands on operators, which may include board awareness, screen navigation, or the need to manipulate multiple variables. **Step 2b** requires identification of event attributes, such as magnitude of an event, rate of evolution of an event, and the nature of recovery from the event. **Step 3** requires selection or creation of scenario events that meet the requirements defined in **Step 2**. These events can range from failed automation to removal of key display systems to deviation from standard operating procedure (SOP). **Step 4** requires review of the selected event and associated higher level attributes of the scenario with SMEs and stakeholders, which then informs iterative review and refinement. **Step 5** requires instantiation of all of the necessary details to create an operational simulation. Pilot testing (**Step 6**) provides essential data to correct, refine, and augment the scenario, often requiring the developer to revisit earlier assumptions and decisions. The data extracted from the interviews appeared to support the Scenario Development Process delineated in **Figure 1**. However, further research will be necessary to validate the sequence of steps within the flowchart, to identify missing steps, and to assure that the process is sufficiently generalizable for many types of HSI as well as for different NPPs.

Next, we aimed to verify the specific attributes of scenario design first articulated in our literature review. Extraction and coding of the interview data identified scenario attributes in 10 of the 12 categories from the literature review (**Table 3**). The last two categories, HSI comprehensiveness and Risk significant human factors were not discerned from the available interviews. Additional questions specific to these two scenario attributes will be used to ascertain their relevance to HSI design in future interviews.

This study has several limitations. First, the literature on simulation scenario design, particularly in process control, is quite limited and using this as a foundation for our initial interview guide may have inadvertently led us to overlook one or more key aspects of scenario design. However, the expertise of one of the authors (MBW) in scenario design for healthcare simulation helped us to identify some issues not revealed in the literature that were added to the interview scripts. Second, we have thus far conducted only a limited number of interviews at a NPPs owned by three utilities. Further, those interviewed were predominantly experienced in simulation scenario design and delivery for purposes of CRO training and, to a somewhat lesser extent, evaluation. While we framed the interviews to elicit information about scenario creation for HSI evaluation, this may have limited or biased our results. Finally, the interviewees were inconsistently familiar (and less commonly operationally experienced) with the full spectrum of modern HSI technologies under development. For example, the identified differences in the design process for scenarios for HSI design versus CRO training/assessment may actually be greater than observed. Future research will require interviews of a larger, more diverse sample of scenario developers including those with specific expertise in simulations for HSI evaluation. Further, to make the ontology more useful, we need to further refine and augment the scenario development flowchart. We are now using a card sorting methodology to allow interviewees to organize the Steps and scenario attributes into a checklist for designing scenario for different purposes.

5. CONCLUSION

We have taken the initial steps to develop an ontology for simulation scenario development specifically to aid in HSI design, evaluation, and deployment. A complete ontology will aid the nuclear industry in evaluating new technology and performing ISV for control room modernization efforts, thereby improving the safety, reliability, and efficiency of the existing fleet of NPPs. The next step will be to conduct additional interviews to expand and generalize the ontology. We also plan to create a usable checklist to aid scenario developers.

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