HUMAN FACTORS CASE STUDY: AN ITERATIVE APPROACH TO VERIFYING AND VALIDATING A NEW SUITE OF REACTOR INSPECTION AND MAINTENANCE TOOLING

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ABSTRACT

An iterative approach was taken to perform the HF Verification and Validation (V&V) activities for a complex set of reactor inspection and maintenance tooling equipment known as the Bruce Reactor Inspection and Maintenance System (BRIMS). This paper is divided into the verification activities (of Human System Information Task Support and Design verifications) and the validation activities. The validation method used a graded approach by breaking validation activities into early usability testing and high fidelity validations. Early usability testing, allowed for issues and design concepts to be identified and explored. High fidelity validation activities tested that the final design requirements and operational goals of the system were met in the production equipment. The validation method has been described in detail by depicting the following: task selection criteria, tools, performance measures and data collection. Validation results demonstrate the benefits of the graded approach as issues were to be identified early in the design process, improvements were made during detailed design and additional testing could confirm that issues were resolved prior to commissioning. To capture and share the success of this iterative V&V approach lessons learned have been created for use in future V&V projects.

Key Words: validation, verification, nuclear reactor tooling, lessons learned

1 INTRODUCTION AND BACKGROUND

The Bruce Reactor Inspection and Maintenance System (BRIMS) is a Bruce Power 8 unit site-wide project aimed at the reduction in outage time at both Bruce A and B CANDU[1] nuclear power generating stations, reduction in accumulated dose to maintenance staff, and complete fuel channel inspection and maintenance within a repeatable and deterministic timeframe. BRIMS was developed to replace three existing, remotely operated inspection tooling systems and establishes a common delivery and inspection process which can be deployed and utilized during planned maintenance outages. The BRIMS project covers the design of eight new subsystems (the engineered sub components that make-up BRIMS), modifications to existing facilities (e.g. fuel handling interfaces in the main control room) and is required to deliver existing inspection tooling without modifying the existing tooling design. Each BRIMS subsystem must be able to function according to their design requirements and work in conjunction with other subsystems to complete the overall BRIMS inspection outage.

Early in conceptual design, Bruce Power identified Human Factors (HF) as a key stakeholder which would help achieve the BRIMS goals. In accordance with Canadian Nuclear Safety Commission (CNSC) Regulatory Guide G-276 [1] and the guidance found in NUREG 0711 [2] the BRIMS HF team performed

[1] CANada Deuterium Uranium (CANDU) is a pressurized heavy water reactor used to generate electric power and allows scheduled maintenance outages for inspection and maintenance of the fuel channels.

the following analyses over the course of three years: Operating Experience (OPEX) review, Functional Analysis (FA), Task Analysis (TA), Staffing and Qualifications (in the form of a proposed Operational Basis), Human Reliability Analysis, Human System Interface (HSI) Design analysis, Input into procedures and training development, Verification and Validation (V&V), and Design implementation. Human performance monitoring has been covered under the existing Bruce Power system. These HF analyses focused on both the individual BRIMS subsystems and the interaction between multiple subsystems.

1.1 Objective

The purpose of this paper is to describe the approach used for the Verification and Validation (V&V) of BRIMS and to identify key lessons learned which can be used by future HF projects. This paper will identify how the V&V approach ensured the final design met HF requirements and guidance, how the design achieves safety goals and operational goals (such as increased productivity and efficiency of the tool execution), and finally, how the HF approach maximizes utilization of the testing resources while minimizing time commitments for HF evaluation.

2 METHOD

The V&V approach was developed in accordance with CNSC G-278, Human Factors Engineering Program Plans Regulator Guide [1]. For the purposes of this paper, the following terms are defined as follows:

***Verification*:** The process of demonstrating that equipment and system have been designed as specified and that adherence to HF has been maintained.

Usability testing: The process of iteratively conducting user testing throughout the development of any system. Users are presented with a prototype design and asked to perform tasks while observers collect data.

***Validation*:** The process of determining the degree to which the human-machine system design and supporting mechanisms facilitate the achievement of overall safety and operational goals.

The BRIMS V&V activities were based on a comprehensive approach to emphasize the iterative nature of the integration between the HF analyses, engineering design activities, project design requirement testing and the verification and validation activities. This was accomplished by utilizing the relationship between the HF analyses with the HF V&V activities and identifying and subsequently leveraging the BRIMS project activities in order to complete the HF V&V activities. This is mapping is shown in Figure 1 and will be elaborated further in this paper.

2.1 Verification

The approach for the BRIMS verification was adapted from NUREG-0711 [2] and used both HSI Task Support Verification and HF Design Verification.

2.1.1 HSI Task Support Verification

HSI Task Support Verification is described as the confirmation that the HSI provides the alarms, information, controls, and task support (defined by tasks analyses) needed for personnel to perform their tasks. This verification was considered at both the subsystem level and the system level which looked at a series of tasks employing multiple subsystems in a work flow. As shown in Figure 1, this was performed by an HSI Review against HF Analyses (human information needs derived from the FA and TA), Design Reviews (50% and 90% design milestones) and the station level review.

The most effective approach to understand the complexity of BRIMS was using storyboards to perform a station level review to outline the work flow for outage activities. Storyboards pictorially described the placement of all BRIMS equipment for each operational step. These storyboards were produced early in detailed design and were subsequently expanded throughout the detailed process as subsystem design became finalized.

2.1.2 HF Design Verification

The HF Design Verification is the confirmation that the design of the HSIs conform to HF guidelines. The Design Verification was conducted iteratively as the design progressed and occurred through the review of documents, verification during prototype testing and post assembly tests.

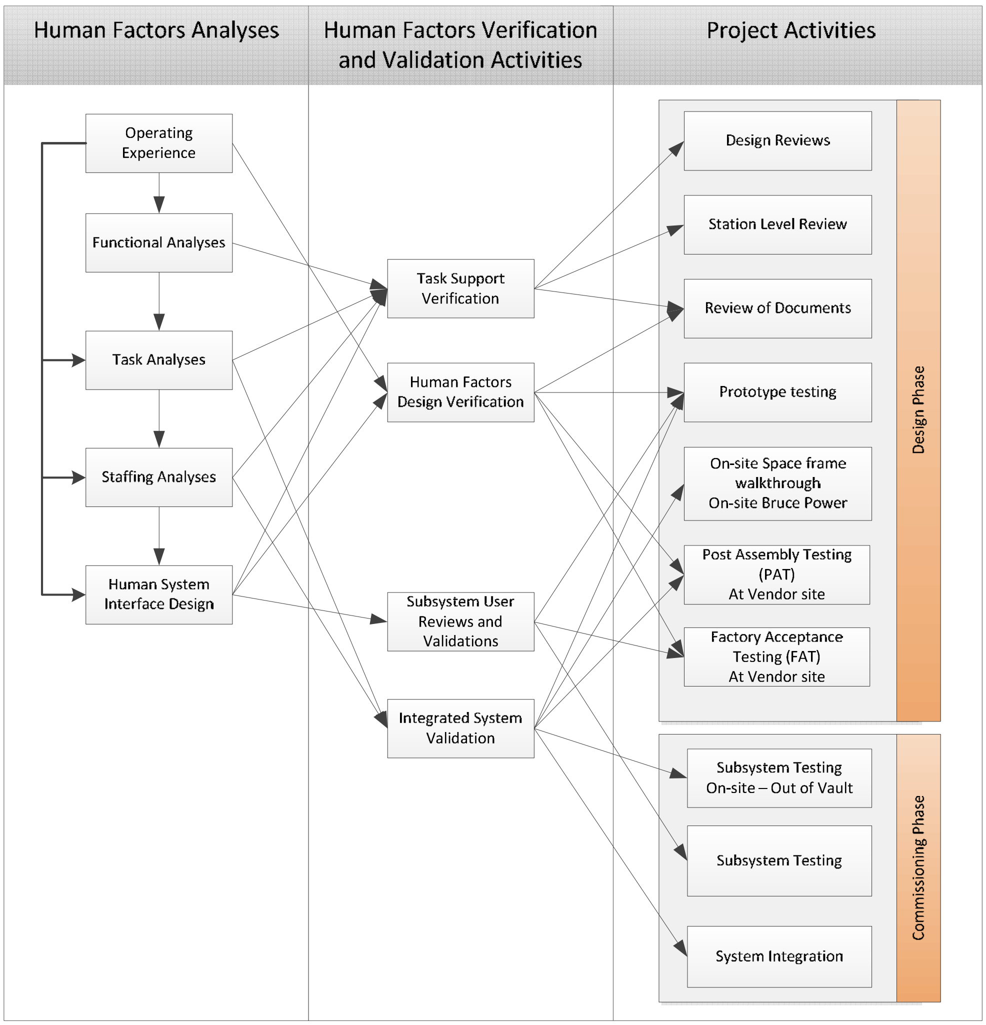

Figure 1 - Mapping of HF Analysis to V&V and Project Activities

2.2 Iterative Validation Activities

Validations were performed iteratively throughout the BRIMS project with prototypes being used early in the design to test early HSIs, concepts and draft task workflows. By performing testing early in the design, system requirements could be confirmed or further refined which mitigated the risk of engineering rework and schedule delay. Early validations focused on the subsystem tasks while later validations focused on the system as an integrated whole.

Validation activities as described by CNSC G-276 [1] and NUREG 0711 [2] were further broken down into usability testing and high fidelity validations. Usability testing activities were distinguishable from validations as they were conducted throughout the design process (often with prototypes) and allowed for issues and design concepts to be identified and explored. Alternatively, high fidelity validation activities tested the final design requirements were met and confirmed that the operational goals of the system were met in the production equipment.

Table I in Appendix A further describes the usability testing and high fidelity validations approaches by describing the application of the criteria using CNSC G-278 validation elements of: approach, location, tools, limitations, techniques, users, training, performance measures, data collection and analysis.

During detailed design, validations activities occurred at vendor sites with early production equipment and early HMIs. Testing focused on the subsystem operations and provided opportunities to implement recommended design changes based on usability findings and user feedback. Subsystem validation activities were generally integrated into existing technical tests such as post assembly testing and factory acceptance testing which provided access to end users, designers and allowed for thorough testing of the subsystems. As detailed design transitioned into commissioning, high fidelity validations were able to focus on the tasks which involved multiple subsystems. As a result of the validation activities, improvements to design, task flow and procedures were recommended.

Usability testing and high fidelity validations which failed to meet performance measures pass criterion, were further analyzed to resolve identified issues. Once resolutions were implemented, a final high fidelity validation took place. Once subsystem designs passed usability testing and high fidelity validations, the validation focused on the relationships between subsystems and eventually towards the BRIMS system as an integrated whole.

2.2.1 Operational Scenarios

Operational scenarios selected for usability testing and high fidelity validations were based on the following criteria:

- availability and completeness of testbed tools (prototype vs. production equipment),
- frequency of tasks performed,
- complexity of tasks,
- criticality of tasks,
- tasks with known issues as identified by previous HF Analysis and
- scenarios where operators must respond to potential equipment failures or potential degraded conditions.

The criticality of tasks was selected from the perspective of: personnel safety, reactor safety, outage schedule, and asset and equipment protection. The BRIMS failure mode and effects analysis (FMEA) was reviewed to ensure all tasks identified with a high risk score were included in the validation scenarios

2.2.2 Tools

Prototypes and mock-ups used for validation activities ranged in complexity from simple wooden or metal spaceframes on casters (used to mock-up the three dimensional space occupied by subsystems) to a robust prototype which modelled some of the system functionality, limitations and physical characteristics of the production subsystem. In addition, some early low fidelity prototypes were later improved to more accurately model the limitations; for example the wooden spaceframes were later wrapped in opaque plastic to reflect the limited line of sight.

Subsystem testing occurred at either the subsystem vendor facilities or at the integration facility whereas all integration activities and outage simulations were conducted at the integration facility. This integration facility contained a full scale mock-up of the most limited dimensions of all Bruce A and Bruce B reactor vaults and was later enhanced to identify and mock up common vault nuisances (i.e., protruding equipment, air hose plugins, etc.). Appendix A provides additional details on the on the use of validation tools.

Performance Measures

Task completion, usability, workload, timeline analysis, and situational awareness were used as performance measures to provide a basis for evaluation of the interface and task design. Pass criteria for the specific performance measures were as follows and data collection is discussed in section 2.2.3:

- Pass criterion for the task complete measure was 75% of the task completed. The pass criteria was not 100% for these evaluations to account for unfamiliarity with the tasks, unfamiliarity with BRIMS and the limitations of the validation exercise.
- Usability pass criteria was an average score on all usability questionnaire questions > 75% and an average score on each question > 50%. A secondary pass criterion of 80% of users ranking each question at 75% or above was also used to identify tasks which were considered as simple and frequently conducted. All task with low usability scores would prompt additional HSI analysis to resolve the source of the low scores.
- Workload as a subjective measure was captured by having the participants rate their own level of workload during a task using the NASA Task Load Index (NASA TLX) questionnaire. A pass criteria for subjective workload was ratings of >75% on a subscale dimension (e.g. mental demand, physical demand, effort etc.), where 100% represents "very high". Where workload was high and could not be resolved through HSI design improvements, task reallocation, additional users or additional skills and qualifications were often recommended.
- Timeline analysis was used to further assess workload given the premise that workload is proportional to the ratio of the time occupied performing tasks to the total time available. Workload evaluated based on time had a pass criterion of 75% and below, workload assessed to be greater than this was reviewed in detail.
- Pass criterion for situation awareness is the correct response to situational awareness questions of >75% for a task. Situational awareness questions were limited to predefined hold points where the task could be interrupted to administer questions without having an impact on the timeline analysis.

Based on these performance scores the HF Specialist would determine the overall validation result as "pass" or "fail". A failing score would either result in additional analysis resulting in design or task improvements. Once improvements were implemented subsystem/system was re-validated or dispositioned based on additional HF Analysis and project limitations. Where the pass criteria was not met for all performance measures an HF Specialist could still provide the validation with a "pass" score with justification based on the additional analysis.

2.2.3 Data collection

The data used to assess the performance measures described above were collected as per the following:

- Task completion: Task completion was identified as how much of a predefined task could be successfully completed by users. The goals for completion and task steps were documented in storyboards, procedures or testing plans and the HF Team scored task completion by how far the user could progress through the task steps identified in these documents.

- Usability: Users identified their agreement to specific usability questions by identifying their response along a continuous scale from Unacceptable (0%) to Excellent (100%). The scale had descriptive anchors markers (unacceptable, poor, adequate, good, and excellent) at every 25% to help guide the participant. Full definitions of each anchor were included in the footer of all questionnaires. The questionnaire contained specific questions tailored to the system/subsystem HSI and task being performed. Generally, the usability questionnaires contained the following topics: ease of task execution; accessibility to equipment, ability to provide system control, feedback associated with each action, as well as overall usability of the system.
- Workload: Workload questionnaires utilized the NASA TLX, which is a ten point scale (from low to high) with mid-point anchors in between the major markings. The NASA TLX assessed user workload having users identify how demanding the task in terms of: information on the: mental demand; physical demand; temporal demand; overall performance[2] effort; and frustration level. These subscales are then combined to provide an average workload score for the task. Workload was also collected by performing a timeline analysis during the final full system validation based on the understanding that workload is proportional to the ratio of the time occupied performing tasks to the total time available. The HF team tracked the active working time of all participants. If a participant was occupied carrying out a task 100% of the time interval then workload was scored as 100% in the time interval.
- Task Timing: Due to the integration of HF Validation activities into existing project testing, time for task completion and task steps was carried out by the BRIMS project team for the majority of tests. The HF team reviewed the testing data and investigated further as needed.
- Situation awareness: Situation awareness was assessed as the correct response to task related questions are predefined hold points. Correct answers were measured and indicated good situation awareness and incorrect or no answers were used to identify poor situation awareness. The percent of correct answers per task used to estimate the situational awareness of the user for a given task.

Users were encouraged to think aloud during the testing and time was provided to discuss the task and design after each validation activity. On both questionnaires, space was provided for users to provide additional comments after each question to provide additional justification for ranking. Also users were encouraged to add any additional comments in the general comments section at the end of each questionnaire.

3 DISCUSSION AND RESULTS

3.1 Verification

All verifications performed on the BRIMS subsystems and overall system were completed prior to acceptance testing at Bruce Power and demonstrated that the BRIMS equipment and system were designed as specified and that adherence to HF has been maintained. In addition, all HF recommendations were confirmed as resolved through recommendation implementation or acceptance of a known risk. The first BRIMS outage was performed successfully in 2015 and met the project goals of reducing dose by 71% (26 Rem) and reduced the duration of a standard outage inspection campaign by 73% or 27.4 days. Dose reductions and time savings are realized from improved deployment methods and reduced duration of in vault work, craning and inspections [4].

[2] Note: The values for performance is a measure of workload, therefore a high raw performance score would lead to a low workload performance score.

3.2 Validation

Validation activities were broken down into three main categories of usability testing, high fidelity validations on site at Bruce Power, and high fidelity validations off site.

Two system level reactor vault task simulations usability testing activities were conducted at the integration facility and performed early in the design to evaluate the proposed transportation path and placement of equipment during the outage campaign. Early outage simulations were given a passing score and provided opportunities to evaluate proposed workflow, lead to risk reduction during the design process and provided a rough estimate of task timelines.

The early outage simulations demonstrated the importance of having accurate vault dimensions and the need to confirm the largest BRIMS subsystems could physically travel down the proposed transportation path (from the storage position to the vault and within the vault). As a further risk reduction method, a metal spaceframe was created to mock-up the volume occupied by the largest BRIMS subsystem and tested the in and out of vault transportation path of Bruce B Unit 7 during a planned outage. Ultimately the spaceframe travelled from the storage location to the vault and thorough the vault, however due to confusion over spaceframe configurations and schedule issues the spaceframe did not accurately represent full three dimensional space required for portions of the evaluation. While this activity was useful to collect additional vault dimensions and test out proposed workflow this activity was inconclusive from a HF validation perspective and not given a pass or fail ranking.

During detailed design and commissioning the validation focus shifted from subsystem operations to tasks which involved multiple subsystems and improvements to design. The types of recommendations produced also shifted with subsystem validations providing recommendations on design changes and between subsystem operations included recommendations on design, task flow and procedures improvements. Overall twenty seven (27) high fidelity validation activities were completed in this phase and nine (9) of which did not meet the pass criteria due to the following reasons:

- Validation was exploring a proposed workflow, based on the low usability feedback the proposed workflow was no longer selected (one validation),
- Validation did not receive a passing score, improvements were made and task was re-validated with passing score (five validations)
- Validation did not have a passing score based on known design limitations. Risk was mitigated through the use of training and procedures with the possibility of revisiting the design after OPEX from the first outage campaigns (three validations)

To comprehensively validate how the BRIMS system performed as an integrated whole, a full system validation occurred in the form of a dress rehearsal mock outage. This dress rehearsal included simulated personal protective equipment (PPE), full production equipment, outage end users, communication headsets and production procedures. The main focus of the mock outage was to perform a timeline analysis to confirm workload scores and to confirm tasks with previously identified issues had been successfully improved. Ten validations were performed during the mock outage with two validations failing to meet the pass criteria. Both failed validations were due to design limitations due to late scope additions and the task could not be further modified prior to the first campaign. Risk was mitigated through the use of training and procedures, and the design was re-analysed after the first campaign to improve the usability of the systems. As of February 2017, BRIMS has been successfully utilized in four outage campaigns in both the Bruce A and Bruce B generating stations.

In total, 45 validation activities were performed for the BRIMS project, these validation activities resulted in which resulted in 163 HF recommendations which were implemented or dispositioned prior to site acceptance testing.

Phase		Subsystem tasks	Subsystems relationships	Integration of subsystems
Preliminary	**User Reviews and Usability Testing - Prototype and Risk Reduction Testing**			
	Outage Simulation and Space Frame User Review			X
	Outage Simulation - Logistics Testing			X
	Outage Simulation - Nuisance Testing			X
Detailed design	**Integrated System Validation On-Site**			
	Unit 7 Delivery System Space frame Deployment			X
	Integrated System Validation Off-Site			
	Stage 1 - Technical Tests with some prototype equitment			
	Delivery System HMI Evaluations	X		
	Change of Delivery System Configurations (HMI and Mechanical)	X		
	Delivery System Manual Drive of Mechanisms	X		
	Equipment Wrapping and Egress of all subsystems	X		
Commissioning	Aligning Tool Change Cart with Delivery System		X	
	Movement of Connected Subsytem from Storage to Operation Positions		X	
	Cabling Connections - Subsytems		X	
	Craning Delivery System onto Positioning Mechanism		X	
	Manual Delatch of Delivery System		X	
	BRIMS Inspection Tool Operations on Tool Change Cart		X	
	Delivery System Homing and Locking to Reactor Mock Up		X	
	BRIMS Inspection Tool Operations on Channel and Calibration at Tool Change Cart		X	
	Stage 2 - Mock-Outage production equipment with full PPE			
	Equipment Ingress			X
	Tool Change Cart Initial Alignment with Delivery System			X
	Tool Change Cart Initial Set Up			X

Figure 2 - Examples of BRIMS Validations and Validation Focus

4 HF LESSONS LEARNED

The HF Involvement in the BRIMS project was highlighted as good performance in the Bruce B Operational Safety Review Team (OSART) programme report as completed by the International Atomic Energy Agency (IAEA). In recognition of the success of the BRIMS V&V approach the BRIMS HF team has created the seven most important lessons learned to identify insights which can be applied on future projects.

LL 1: Search for opportunities in existing project activities where HF can expand the testing scope to perform HF validation activities.

Early in the design, the BRIMS HF Team reviewed the BRIMS testing schedule, and identified project activities which could be utilized as validation opportunities. Usability testing and high fidelity validation requirements were compared against the existing test plan to determine the testing scope modifications required to allow testing activities to be credited as validation activities. Generally, addition of HF into the testing scope was minor and included incorporating more representative end users or including testbed mock-ups. By capitalizing on planned project activities, the HF team used existing resources and testing dates to complete HF goals thereby leading to a project schedule and resource savings and guaranteed access to testbeds, designers and end users. Additionally, by defining the HF expectations early in the process, subsequent project testing efficiently incorporated HF requirements such that HF was embedded in the testing process.

LL 2: Perform validations early and iteratively to evaluate the proposed design, gather feedback and focus later validations.

By using operational scenarios and a task-based approach, validations provided the design and development teams an opportunity to understand issues and explore possibilities before subsystems were manufactured. By identifying issues before the design is finalized, design issues can be resolved and improvements can be incorporated. This leads to minimizing rework and reduces design, schedule and financial risk. In addition to providing input into engineering design, early testing can also identify improvements in the testbed, the supporting management systems, training and procedure development or identify the need to include additional testing.

LL 3: Validation testing can start with low fidelity mock-ups and enhance mock-ups during the design.

Early BRIMS mockups were simple, but effective at testing early spacing and workflow issues within the mock-up vault. As the design progressed mockups were enhanced (i.e. wrapping the spaceframe in plastic wrap to represent the inability to view through the spaceframe) and were eventually replaced by working prototypes or early production equipment. Early mockups and basic testbeds should be used early in the design to allow for early incorporation of findings and testing of ideas.

LL 4: Validation scenario selection should apply systematic criteria to ensure coverage of critical operation scenarios.

Scenario selection should include the complexity and criticality of tasks from the perspective of personnel safety, reactor safety, outage schedule, and asset and equipment protection. Project documents which look at the complexity and criticality of task, such as the FMEA should be used as a basis to ensure high risk tasks are validated.

LL 5: A simplified tool (e.g. storyboards) should be used to encourage review and consensus across a wide variety of stakeholders.

Having a clear depiction of the proposed operational steps, allowed stakeholders to easily review and provide feedback on proposed steps. This encouraged more stakeholders to provide comments and ensured all stakeholders were aligned. A storyboard or similar tools should be used for large scale projects with multiple subsystems as an efficient means of communicating across the project team and to facilitate engagement with new stakeholders.

LL 6: Perform a high fidelity validation with proper PPE to validate the system as an integrated whole.

In order to validate the system as an integrated whole, a high fidelity validation should occur with proper PPE and representative end users. This provides a final opportunity to review the HSI, workflow and procedures to confirm that there are no unresolved issues or new findings. HF recommendations at this stage were limited to procedures and training however there is benefit to identifying and incorporating these improvements prior to the system being used in production. Additionally, by scheduling a final validation end users were able to train with production equipment in PPE and HF was able to provide direct input into the training process.

LL 7: Field nuisances should be mocked up and testbed assumptions should be validated.

Field nuisances should be mocked up (with varying degrees of fidelity given the design phase) during testing to prompt the end users, design team and HF specialist to focus on how the system will interact and impact in its operating environment. Examples of items which are often overlooked in early testing but should be mocked up include cable connections, air hoses and areas that block a user line of sight (such as stairs). Mockup of these field nuisances can be low fidelity such as rope for cables and plastic covered spaceframe for stairs. These types of field nuisances can negatively impact the workflow and can be easily overlooked in drawings or not sufficiently accounted for in procedures. Field assumptions should be validated to ensure all nuisances and field details are accounted for.

5 CONCLUSIONS

Overall, the HF verification and validation evaluations were iterative and robust which supported BRIMS design and facilitated the ability of system users to achieve the overall safety and operational goals. Thus far, the BRIMS system has been used successfully during three outages and this success can be partially attributed to the HF and project testing activities described in this paper.

6 REFERENCES

[1] CNSC Regulatory Guide G-276, Human Factors Engineering Program Plan, 2003.

[2] NUREG-0711, Rev. 1, Human Factors Engineering Program Review Model, 2002.

[3] CNSC G-278 Rev. E Human Factors Verification and Validation plans, 2003.

[4] NSNI/OSART/016/188 Report of the Operational Safety Review Team (OSART) Mission to the Bruce B Nuclear Power Plant, 2015.

APPENDIX A

Table I – Criteria for Defining a Usability Testing or Validation using CNSC 278[3]

	Usability Testing	High Fidelity Validations
Approach	- Primer with users to outline the HF process, HF objectives and provide an overview of selected scenario. - Users complete selected scenario using available tools with situational awareness and timing occurring were applicable. - Distribution and completion of questionnaire(s) - Follow up interviews and discussions based on user feedback and observations	
Location	- Subsystem vendor facility or integration facility	- Integration facility
Tools	- HF Questionnaires (usability questionnaires) - Various other items as needed (e.g. measuring tape, stopwatch etc.) - Camera - Draft procedures (e.g. operating sequences, test procedures, work instructions, work flow diagrams etc.); - Mock-up testbed - Test rigs (where applicable) - Prototype tools and software - Spaceframes - Storyboards	In addition to the usability testing tools the following were used: - High fidelity mock-up testbed - High fidelity Test rigs (where applicable); - PPE - Production equipment - Nuisance equipment (cables, air hoses, etc.)
Analysis Limitations	- Mock-up facility used (better lighting, communication easier) - Space frames and prototypes used - PPE largely not used - Prototype Software used - Transportation of prototypes are easier than production - Nuisance equipment not mocked up	- Mock-up facility used (better lighting, communication easier) - Limited PPE used - SA only allowed at hold points to avoid impacting timing - Procedures not finalized - Transportation of equipment easier in mock-up facility
Techniques	Field Observations , Process Tracing , Structured Interviews, Unstructured Interviews	
Users	Experienced representative end users who have knowledge of fuel handling and reactor inspection and maintenance activities and were not involved in the BRIMS design process.	
User Training	Participants were provided with information relating to BRIMS or it's subsystem as required per the selected scenario and HSI being evaluated.	
Performance Measures	Task completion, Usability, situation awareness	Task completion, Usability, workload, situation awareness, timeline analysis
Data Collection and Analysis	Data were collected based on participant and observer comments with follow up structured and unstructured. Questionnaires were completed by users and scores were analyzed using descriptive statistics as the number of participants was too small for inferential statistics.	

[3] Identical information between evaluation types have been represented by a merged cell.