AN INTERACTIVE COMPUTER-BASED TRAINING AID FOR NUCLEAR REACTOR REFUELLING OPERATIONS

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ABSTRACT

An interactive computer-based training aid is being developed for operator training in emergency recognition and response to events involving loss-of-coolant during refuelling operations for the NRU nuclear research reactor.

The training aid incorporates both conceptual and functional training components. Conceptual training consists of sequenced presentations of text, graphics and animations to explain the fuelling-system configuration, operations, abnormal events, and recovery procedures. Functional training consists of procedural practice with an interactive simulation of refuelling operations presented on a multi-window display.

This paper outlines the project objectives, discusses the approach taken to characterize the training material, describes key features of the training aid and relates our experience in coupling hypermedia and knowledge-based tools for the implementation of an interactive training simulation.

BACKGROUND

Well-trained personnel are essential for the safe and effective operation of nuclear and process facilities. To maintain operational skills at high levels of performance, personnel require opportunities to practice learned behaviours and receive feedback on their performance.

Beyond initial familiarization and skills development training, most ongoing skills practice, reinforcement, and assessment occurs during the performance of daily operational tasks. This is, in effect, "on-the-job" training. This is an acceptable practice for skills performed on a routine basis. However, for skills that may be used only infrequently, such as emergency procedures to ensure plant safety and protect plant investment, an alternative means of skills maintenance must be provided. Commonly, periodic refresher training is used to maintain these skills.

Refresher training in the use and practice of infrequently used skills is usually performed outside of normal operational duties. This training often consists of a mixture of supplementary self-study and/or conventional lecture-format instruction, and operational practice. The purpose of the self-study and instruction is to reacquaint personnel with performance objectives, skill principles and characteristics, equipment configurations, and event scenarios and indications. Operational practice provides immediate opportunities for skill development and reinforcement after self-study or instruction.

Sometimes this operational practice can be performed with the plant equipment during periods of non-production. In other cases, simulators are used for operational practice:

- for facilities with high production demands,

- where the practice of specific skills could risk personnel safety and plant investment unacceptably, or

- where it is not technically or economically feasible to create the appropriate training scenarios with the normal configuration of plant equipment.

Full-scope simulators that replicate the full physical and functional characteristics of control interfaces have been extensively used in the civil aviation, military and nuclear industries for operational practice training. However, experience has shown that full re-creation of scenario and equipment performance is not necessary to address most training requirements. For example, nuclear industry experience with control room operator training has shown that 75-80% of the training needs can be met with only 25-30% of the full-scope control room simulation capability (1,2).

Traditionally, even limited-scope or part-task training simulators have not found wide acceptance, due to the high cost of software and interface development, low simulation fidelity, and narrow instructional scope. However, recent advances in instructional design approaches and microcomputer-based computing technologies have created new opportunities for developing low-cost, yet highly effective, computer-based training applications (3). The key components of these advances are:

- instructional strategies that permit on-line adaptation of instruction to suit individual student learning styles, thus providing more effective instruction delivery,

- highly productive software development environments, such as hypermedia and customized training application authoring tools that offer lower application development costs,

- high-performance and low-cost computing platforms that enable improved simulation fidelity and real-time performance for moderate to complex applications, and

- low-cost, interactive graphical user interfaces that enable the development of interfaces to closely mimic the physical and performance characteristics of plant equipment, thus improving application fidelity.

As a result of these developments, it is now feasible to apply computer-based simulator training to a wider range of applications.

At Chalk River Nuclear Laboratories, a joint project was undertaken by the NRU Operations, and Instrumentation and Control Branches to explore the technical feasibility and cost-effectiveness of developing microcomputer-based simulators for operations training.

REQUIREMENTS

At the onset of the project, it was decided to develop a computer-based training aid for infrequently used emergency procedures associated with refuelling operations. To provide a procedural practice capability, an interactive simulation of refuelling operations was developed.

The following requirements were established for the training aid:

- the scope would be limited to training for emergency recognition and response to loss-of-coolant during refuelling operations,

- the training methods would consist of sequenced presentations of background training material, and an interactive simulation for practice in event recognition and recovery response procedures,

- trainees would interact with the simulation by means of an interactive computer display that would mimic the physical representation and functionality of the NRU Fuel-Rod Flask instrumentation panels,

- the interactive simulation would execute in real-time and could be interrupted, and

- the interactive simulation would be developed using a hypermedia programming environment to minimize development effort.

Development was partitioned into three project phases. The first phase was to develop the computer-based mimic displays of the Fuel-Rod Flask instrumentation panels and simulation interface, the underlying simulation, and implement the symptoms and recovery procedure for a single loss-of-coolant initiating event. This functionality would provide sufficient demonstration of the training capability and effectiveness of an interactive simulation for procedural practice. In addition, the real-time performance capabilities of the programming environment would be sufficiently tested.

TRAINING MATERIAL DEFINITION

Two analyses were used to characterize the detailed operational and training information for the training aid at the beginning of the project. First, the event symptoms characteristic of a loss-of-coolant event were identified and referenced to a common timebase; the symptoms observable to the fuel-rod handling crew were selected for later incorporation into the interactive training simulation.

Second, a function analysis of recovery procedures was performed. A function analysis is a top-down method of identifying and organizing the functions required to achieve a specific objective (4,5). In this case, the analysis provided a method for relating operational goals to specific recovery actions, and identifying the subset of refuelling console instrumentation and controls required for event recognition and response training. The analysis also provided an excellent familiarization with refuelling principles and operations, event characteristics, and recovery procedures for the training aid developers.

A recovery procedure display incorporating information from the functional analysis is shown in Figure 1. The event the recovery procedure is applicable to and the operational goal of performing the procedure are shown across the top of the display. Specific operator recovery actions are listed in sequence down the middle of the display, highlighted in bold type.

The left side of the display conveys the purpose of recovery actions. The intermediate functional relationships that link the contribution of each recovery action to the achievement of the overall operational goal are represented in the three sub-goals, objectives and sub-objectives columns.

The right side of the display conveys how each recovery action is performed and what confirmation of successful performance is available through the equipment interface. Each recovery action identifies the equipment to be controlled or monitored. To the right of the recovery actions column, two columns identify the panel location of the instrumentation used and the expected observable result of performing the recovery action.

Both analyses were developed by interviewing reactor operations and training personnel, consulting equipment and operating manuals, and observing "walkthroughs" of simulated event recognition actions and recovery procedures with the NRU fuel-rod flask instrumentation panels. The completion of these analyses required one quarter of the overall project budgeted effort.

TRAINING AID DESCRIPTION

The training aid was designed to incorporate both conceptual and functional training components. Conceptual training consists of sequenced presentations of text, graphics and animations to explain the fuelling-system configuration, operations, abnormal events and recovery procedures. This training will familiarize the trainee with refuelling operations and establishes “mental models” for operational use in analysing refuelling operations. Also, it will characterize the symptoms for specific loss-of-coolant events and relate recovery actions to specific operational objectives. Trainees will review this material prior to working with the interactive simulation for procedural practice. The conceptual training features will be developed in later phases of the project.

Functional training consists of an interactive simulation of refuelling operations presented on a multi-window computer display. Three simulation modes provide a graduated transition from an off-line, guided walkthrough of recovery procedures to an unaided, real-time replication of loss-of-coolant events. This training component provides real-time procedural practice in event recognition and recovery, and a standardized means of evaluating student performance.

The simulation interface comprises a single computer display for information presentation and a mouse pointing device and keyboard for input. Information is presented to the trainee via both multi-window displays and menu selections. Trainee control of and interaction with the simulation is through direct manipulation of displayed objects via mouse control.

The primary simulation display is shown in Figure 2. The main display area is divided into three window regions. On the left of the display, one window contains a diagram showing the relative positions of fuel rod and coolant level in relation to the reactor and fuel-rod flask. During event simulation, the fuel rod and coolant level are animated to show their position as determined by the underlying simulation. This display was created to make visible to trainees the direct results of recovery actions on fuel rod and coolant level movements. During actual reactor refuelling, the operator must infer the relative positions of the fuel rod and coolant from panel instrumentation.

The main portion of the display contains a second window that replicates the physical representation and functionality of two instrumentation panels from the fuel-rod flask instrumentation panels. One view shows the Extraction panel, which contains instruments and controls for the fuel-rod hoist. The other view shows the Circulation panel, which contains the instruments and controls that affect flask coolant level. Not all panel instruments have been fully implemented. Instruments and controls required for event recognition and response training are fully functional. Other panel instrumentation is identified and labelled, but has no functionality. This approach was taken to ensure the visual fidelity of the instrument panel interfaces, yet limit the development effort.

Only one instrumentation panel is shown at a time, and the selection is determined by the trainee. At the fuel-rod flask, both panels are separated spatially and an operator must physically turn to view the alternative panel. Thus, the presentation of one instrumentation panel view at a time, and the capability to select between panel views, mimics the action of an operator turning to view the alternative panel.

During an event simulation, the trainee carries out recovery actions by selecting panel controls using a mouse pointing device. Visual and auditory feedback for control actions has been built into the interface. For example, switches visually change position and click when activated by mouse command.

Across the top of the display, a third window contains simulation controls and status indicators. Simulation controls in this window provide a means to start, pause, resume and reset a simulation and select either the Extraction or Circulation instrumentation panel views. The simulation status portion of the window indicates the initiating event, the reactor trip state, the simulation duration, and the length and duration of fuel exposure.

A menu bar appears across the top of the display. Menu items provide a means to set-up the simulation conditions (mode and event selection), access reference material, obtain supplementary help, save and re-run simulations, obtain an evaluation of the recovery actions taken, and terminate the application. Each of the four menus can be opened by pointing the mouse to a menu heading, depressing the mouse button, and then dragging the mouse downwards to view the menu items. Menu selections are overlayed in a separate "pop-up" window region on top of the main three windows.

Three simulation modes have been implemented to provide trainees with graduated practice from a guided walkthrough of recovery procedures to real-time event re-creation. The three simulation modes are:

Mode 1 - Guided Walkthrough

The trainee is led through the event recognition and recovery procedure step-by-step. Once started, the simulation automatically pauses at appropriate points and the trainee is prompted with a message explaining the purpose and extent of the next recovery action. Once the correct action is performed by the trainee, the simulation resumes.

Mode 2 - Interruptible Simulation with On-line Help

The trainee is no longer prompted to perform recovery actions. Once started, the simulation progresses in real-time. However, the trainee can pause the simulation and review the reference information via the Help menu selections, as needed.

Mode 3 - Real-time Simulation

Once started, the simulation will progress in real-time and can not be paused. The trainee is expected to perform event recognition and recovery actions with reference to only the instrumentation panel displays. The left-most window display showing the fuel-rod and coolant level positions in relation to the reactor and fuel-rod flask is not visible in this mode.

Two emergency coolant supply valves are required in the recovery sequence but are not located or controlled from the two instrumentation panels. Symbols for these valves have been added to the Circulation instrumentation panel for trainee selection. Once either valve is selected, a photograph of the equipment containing the valve is displayed, and the trainee is prompted to point to the valve location and select the desired valve state as a means of completing valve action.

The training aid was implemented on a Macintosh II computer with a 19" black-white display. The interactive simulation was developed with the SuperCard hypermedia application from Silicon Beach Software and the NEXPERT OBJECT knowledge-based shell from Neuron Data Incorporated. These applications afforded the use of an object-oriented approach to the software design for the interactive interface and simulation. The SuperCard hypermedia environment was used to implement the interactive display interface and the temporal aspects of the underlying simulation. NEXPERT OBJECT was used to implement the simulation decision logic governing the interaction of instrumentation panel controls and instrument behaviour. During a simulation, both applications run concurrently and communicate by passing messages back and forth.

DEVELOPMENT EXPERIENCE

This project was the first experience for the development team in coupling hypermedia and knowledge-based tools for the implementation of an interactive training simulation. The following lessons were learned:

- Close interaction with potential users during application development is essential.

  Our development team included a reactor operations engineer knowledgeable about fuelling operations, who was a potential user of the training application. This close access to operations knowledge was essential during the characterization of operations and instructional information to be included in the application. As development issues arose, opportunities for daily contact with this individual enabled the software developers to be guided by timely user feedback.

- The Function Analysis method is very useful for characterizing training application information.

  The function analysis method was a practical tool for eliciting and relating event and operational knowledge from NRU staff domain experts. We found the use of the functional analysis framework very useful in constraining the work scope and providing focus during knowledge acquisition discussions. The method also provided a reference template for selecting and structuring the pertinent instructional information to be incorporated into the application.

- SuperCard is an excellent tool for interactive interface design.

  The SuperCard hypermedia environment proved to be an excellent tool for the development of an interactive interface. Implementation of the customized equipment controls and animations was straightforward. The programming environment was easy to learn.

- The combination of SuperCard (simulation interface) and NEXPERT OBJECT (simulation logic) provide an excellent environment to implement interactive simulations.

  Alone, the current version of SuperCard is not suited for applications where complex logic or equations must be executed within time constraints of less than a second. The original intent was to use SuperCard for all aspects of the application. However, portions of the application were constrained by the SuperCard environment to follow a procedural paradigm. This resulted in several instances of embedded IF..THEN..ELSE constructs, or the use of complex algorithmic procedures to implement application decision logic that resulted in slow simulation performance. Consequently, we used NEXPERT OBJECT to perform most of the procedural decision-making for the application to lower simulation response time.

- The graphical user interface of NEXPERT OBJECT accelerated application development.

  NEXPERT OBJECT uses a graphic interface to enable developers to encode logic rules. We estimate the simulation logic for this application was implemented in half the time required to develop the equivalent logic by IF..THEN..ELSE or algorithmic constructs in a traditional programming environment. Additionally, the graphical representation of the decision-logic was more readily visible and easier to troubleshoot for the application developers, and easier for the reactor operations personnel to audit. An example of a portion of the decision-logic that determines the fuel-rod flask hoist speed is shown in Figure 3.

CONCLUSIONS

The project has demonstrated that highly effective, computer-based training applications can be implemented by exploiting recent advances in low-cost, microcomputer-based computing technologies. The combination of a hypermedia environment and a knowledge-based shell proved to be an excellent way to implement a real-time interactive simulation for procedural practice.

The Function Analysis method was shown to be very useful for characterizing and structuring the training application information.

Initial client impressions of this limited application and the training potential of interactive simulations, in general, have been very favourable.

Current work is focussed on performing a formal evaluation of the training interface with reactor operations personnel. The objectives of the evaluation are to assess the training effectiveness, the intuitiveness of interface features, and the fidelity of the instrumentation panel mimics and simulation behaviour. Evaluation sessions with a number of reactor operations staff are planned and will involve:

- initial evaluator familiarization with the Macintosh interface characteristics on a separate application,

- pre- and post-testing of the evaluator's subject matter understanding,

- video-tape recording of the evaluator use of the interactive simulation and the collection of verbal protocols, and

- follow-up interviews with the evaluator to solicit subjective impressions and suggestions for improvement.

Following this evaluation, a decision on whether to proceed with further development and field use of the training aid will be made. Current planning calls for the development of the conceptual training material, the addition of more event scenarios, the extension of panel fidelity, and the development of features and measures to assess trainee performance in later project phases.

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FIGURE 1: RECOVERY PROCEDURE DISPLAY CONTAINING FUNCTIONAL ANALYSIS INFORMATON.

Recovery Procedure

Event: Loss of Class 4 power, resulting in rundown of main heavy-water pumps.
Operational Goal: Maintain full cooling to fuel rod by keeping it fully immersed.

Sub-goals	*Objectives*	*Sub-Objectives*	*Step*	*Recovery Actions*	*Device Location*	*Observables*
Limit initial coolant drop in snout of fuel-rod flask.	Apply vacuum above coolant in fuel-rod flask	Start generating emergency vacuum.	1	Switch on emergency vacuum pump.	Circulation panel - lower right.	Vacuum pump ON lamp illuminates.
		Check that vacuum line is open between vacuum sources and flask.	2	Check vacuum line valve V-56 is open and open if closed.	Circulation panel - upper left.	Switch in ON position.
		Use available vacuum from vacuum tank.	3	Open valve V-12 if vacuum tank pressure is below atmospheric pressure.	Circulation panel - center	Vacuum tank pressure initially < 0. Switch in OPEN position.
Return fuel rod to reactor core.	Lower fuel-rod extraction hoist via STANDBY mode.	Start lowering fuel rod.	4	Select STANDBY hoist mode.	Extraction panel - top center.	Switch in STANDBY position.
			5	Start hoist low-volume hydraulic pump.	Extraction panel - top right.	Pump running lamp illuminates.
			6	Start hoist down.	Extraction panel - center.	Rod position in light string lowers.
		Over-ride programmed slow lowering speed.	7	Select medium hoist speed.	Extraction panel - top right.	Switch in ON position.
Ensure continued availability of flask circulation pumps and flask coolant inventory	Prevent gas-locking of coolant pumps.	Select tank-to-tank circulation flow.	8	Switch valve V-8 to tank-to-tank flow.	Circulation panel - center left.	Switch in LEFT position.

Done

FIGURE 2: INTERACTIVE SIMULATION USER INTERFACE.

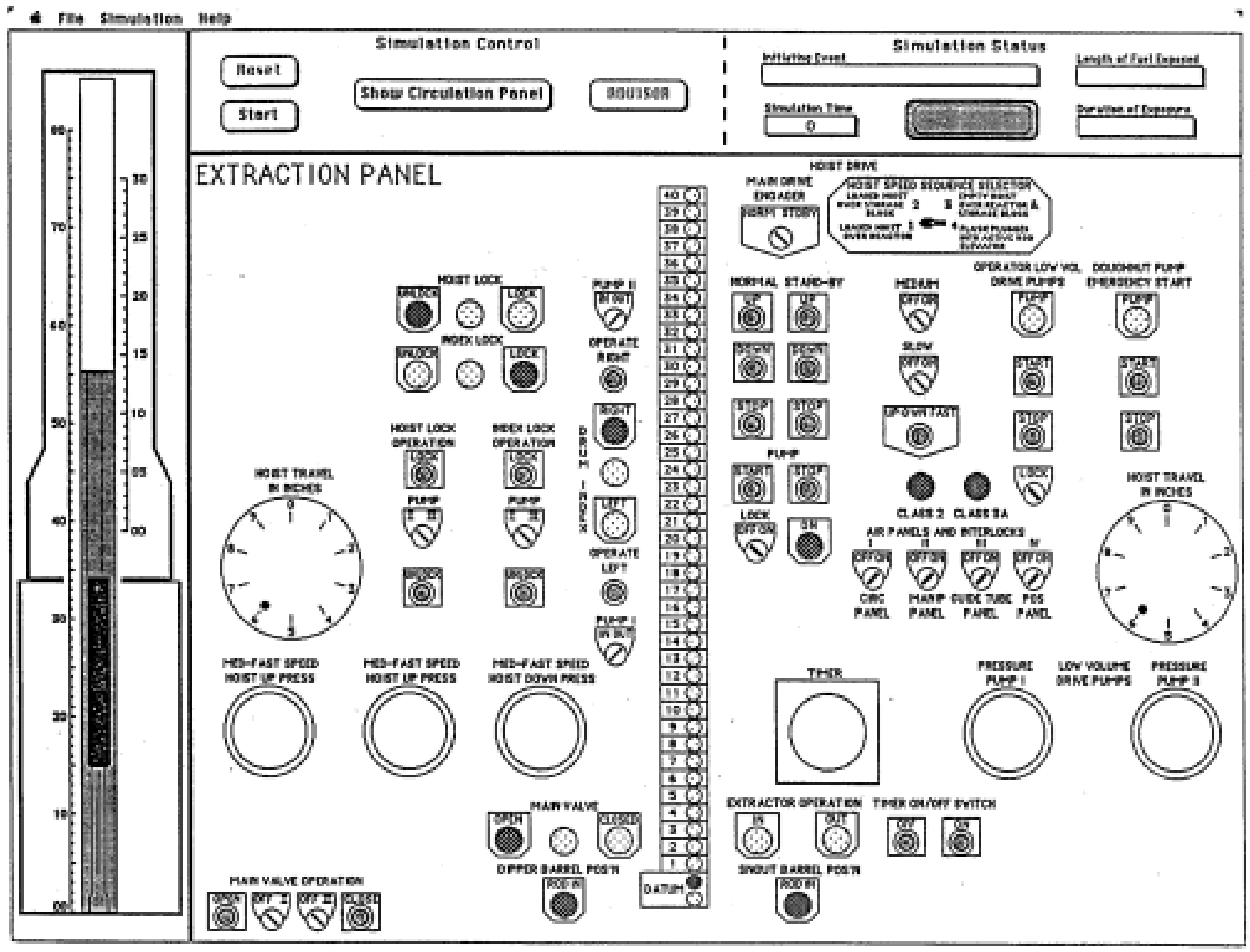

FIGURE 3: NEXPERT OBJECT GRAPHICAL REPRESENTATION OF A PORTION OF THE HOIST CONTROL LOGIC