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Generation IV Nuclear Energy Systems Construction Cost Reductions through the use of Virtual Environments

Task 4 Completion Report: Virtual Mockup Maintenance Task Evaluation

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Applied Research Laboratory (ARL)
Penn State University
P.O. Box 30
State College, PA 16804-0030

Collaborators:
Panlyon Technologies, LLC
Westinghouse Electric Company
Burns and Roe Enterprises

EXECUTIVE SUMMARY

Advances in immersive visualization technology allow for the creation of computer-generated, three-dimensional virtual reality environments. Through the use of a CAVE system, a small group of users can be physically immersed within a full-scale virtual mockup generated from standard Computer-Aided Design (CAD) data. These virtual mockups can be used to provide an effective 1:1 scale review of a space for a small group of users, or to virtually perform human-in-the-loop task simulations to enable improved insight into arrangement, manufacturing, and operational issues.

Using distributed interactive simulation technology, virtual environments hosted on different computer systems can communicate over networks in near real-time. This capability permits, for example, a workstation networked to a CAVE system to be configured to remotely observe the activities of a user within the CAVE. This capability can enable an effective collaboration between a larger group of users than can actually be immersed within the CAVE itself.

The objective of this five-task project is to demonstrate the feasibility and effectiveness of using full-scale virtual reality simulation in the design, construction, and maintenance of future nuclear power plants. The project will test the suitability of immersive virtual reality technology to aid engineers in the design of the next generation nuclear power plant and to evaluate potential cost reductions that can be realized by optimization of installation and construction sequences. The intent is to see if this type of information technology can be used in capacities similar to those currently filled by full-scale physical mockups.

Much of the development of the virtual mockup has taken place at Penn State ARL's SEA Lab facility. The SEA Lab equipment includes a five-sided CAVE in which the computer-generated images completely surround the user. A number of tools allow the user to view and interact with the virtual mockup. Active-stereo glasses, worn by users, allow three-dimensional, stereoscopic images to be viewed. A motion tracking system tracks the user's position in the virtual world. The user is able to navigate freely through the world using a mouse-like device. The wand device facilitates interaction with objects within the image. Together these tools provide the user with a believable virtual reality experience.

While previous work demonstrated that virtual reality can be used in training applications for hazardous work environments, this project aims to extend the previous body of knowledge to include the use of full-scale mockups for NPP training activities. Four virtual mockups were developed during this study, which model training mockups at Limerick Generating Station, Susquehanna Steam Electric Station, and the yet-to-be-built AP1000. The mockups were used to test the technology's applicability to common training tasks in the nuclear industry. Of these tasks, the technology, in its current state, appears to be best suited for pre-job walkdowns, equipment placement activities, and familiarization training. Additional effort will be required in the area of interaction with the mockup to extend the usefulness to other training tasks.

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1 Introduction

The objective of this project is to demonstrate the feasibility and effectiveness of using full-scale virtual reality simulation in the design, construction, and maintenance of future nuclear power plants. Specifically, this project will test the suitability of CAVE virtual reality display technology to aid engineers in the design of the next generation nuclear power plant and to evaluate potential cost reductions that can be realized by optimization of installation and construction sequences. The intent is to determine whether or not this type of information technology can be used to improve arrangements and reduce both construction and maintenance costs, as has been done by building full-scale physical mockups.

2 Task Description

The development, testing, and evaluation of the virtual environment technology for the stated objective are divided into five tasks, to take place over three years. The first task entails the creation and review of a full-scale virtual mockup of a selected space within an advanced nuclear power plant design for use as an experimental testbed. During the second task, the testbed created in Task 1 was used to study the effectiveness of the technology to support the development and evaluation of the modular construction strategy for the selected space. The third task involved developing the methodology and the required tools to perform a prototypical maintenance task using the virtual mockup. The actual maintenance activity study was performed as task four. A fifth report details the work performed on the final task, applying the lessons learned to determine the feasibility of creating a virtual mockup and performing similar activities for a Generation IV nuclear power plant.

Task 4, described in this report, includes the following activities:

- Creation of virtual mockups to conduct task training experiments for NPP training activities
- Development of experiments to evaluate suitability of virtual mockups for training activities
- Performance of experiments to evaluate suitability of virtual mockups for training activities
- Burns and Roe and Panlyon will provide independent assessment of the usefulness of the mockup for training people to perform activities and assessing the arrangement suitability of the plant design for maintenance.

3 Use of Virtual Reality for Training

Visualization technology enables users to view complex data sets, visit facilities before they are constructed, and safely experience hazardous environments. There has been some effort in the past to test visualization technologies in areas related to nuclear power, but the industry, as a whole, has been slow to adopt the technology, most likely due to the expense of the virtual reality (VR) systems and difficulty quantifying benefits that are not subjective.

Much of the past research in VR has focused on desktop applications; however, few have investigated so-called immersive virtual reality on large projection systems that are becoming more common. Some of this previous body of knowledge is introduced below.

3.1 Previous Work in Other Industries

A number of examples of VR-based training systems for hazardous environments exist. Five of these are highlighted below.

3.1.1 Shipboard Firefighting

Researchers created a training simulation of firefighting activities aboard the US Navy's firefighting training ship formerly called the *Shadwell*. The research team created a virtual model of the *Shadwell* and simulated the effects of fire and smoke on subjects wearing a head-mounted VR display (HMD). Navigation was facilitated using a 3-D joystick. Two groups of subjects participated in the experiments; one group trained in the virtual simulator while the second served as a control group that was not trained prior to performing the tasks on the real ship. Subjects were trained to perform two tasks – a navigation task and a firefighting task. In the first set of experiments, the participants trained in the VR simulation of the *Shadwell* had fewer navigation errors and completed the task more quickly than the control group that had not received the VR familiarization training. In the second set of experiments, which required the participants to navigate and extinguish a fire, the group trained in the VR simulation completed both elements more quickly than their counterparts, with a smaller deviation in the completion time. The results of the experiments suggest that VR familiarization training is an effective means of introducing personnel to complex and potentially dangerous work environments. (Tate, 1997)

3.1.2 Team Training

The Fully Immersive Team Training (FITT) system was developed to support research and development of distributed virtual environments for team training. The FITT includes a number of advanced capabilities including a motion model, object manipulation, communication between participants, the use of avatars, and data capture and replay. The training system consisted of a series of networked computers and HMD. The trainee would receive training from manuals then the VR trainer would be introduced. Once the trainees were comfortable with the two systems, they would be immersed in a virtual mission where they would have to work together to successfully complete the mission objectives, which was typically a search for hazardous materials. Measures of effectiveness included speed and accuracy of their search, communication between participants, and proper use of procedures. Participants reported that they felt highly immersed in the environment. (Lampton, 2001)

3.1.3 Mine Safety Training

Denby and Shofield developed a virtual reality system to train mining personnel about working safely in the mine environment. The system was used to train surface-mine truck drivers in safety practices, to train and test new mine workers in safety inspections, and to train and test mine rescue teams in incident response. The Haulage-truck hazard identification system combines realistic mine layouts with dynamic sound, lighting, and physics modeling to reproduce a realistic simulator for haulage-truck drivers, teaching them to identify hazards such as poorly parked vehicles or tailgating situations in the mine. The safety inspection training program presents unsafe situations in the mine, which the subjects must recognize. It reinforces the training by replaying the scenario with all safety equipment in the proper location. Training is flexible and can be focused on preventing common problems seen in the field. Finally, the mine incident training system can be used to train the emergency teams that respond to incidents. The simulation includes a dynamic ventilation model. This system allows users to be placed in dangerous situations without the risk associated with the real situation. (Denby, 1999)

3.1.4 Power Plant Switchyard Training

The ESOPE-VR system was developed in 1995 to train electrical utility workers in switchyard operation and control room evolutions using a desktop VR system, a SGI workstation. The system was developed by researchers at McGill University in Canada and utility personnel from Hydro-Quebec. ESOPE-VR displayed a realistic 3-D model of a utility switchyard, a distribution station, and a control room. The control room model was designed to provide a realistic-looking indoor environment while providing the user with a dynamic environment. The success or utility of the mockup training was not reported; however, this demonstrates an early attempt to use VR for utility worker training. (Garant, 1995)

3.1.5 Safety Virtual Environment (SAVE)

The safety virtual environment (SAVE) was developed by researchers at the University of Linz for OMV AG Schwechat in Austria to train workers to perform hazardous tasks and handle emergencies. The environment consisted of a visual simulation displayed on a HMD, an instructor station, a motion platform, and a simulation authoring tool. The SAVE system enabled an instructor to supervise and control the simulation in real-time. The desktop authoring tool could be used to build scenarios, including geometry and interactions. The programming of the system was an extension of the VRML 97 standard, making it fairly portable to different computer systems. These tools created believable virtual environments for training applications. (Holm, 2001)

3.2 Recent Work in Nuclear Power-related Activities

Recently, virtual reality has received a little more attention in the nuclear field. Some recent examples of virtual reality research in the nuclear industry are highlighted, below.

During the mid-90's, a team at the Argonne National Laboratory looked at using virtual environments for nuclear power plant design. The researchers evaluated a number of products including InSight, Quick Time VR, and the CAVE. They created virtual models of the Sodium Process Facility control room and the Sodium Carbonate addition to the facility in 3-D Studio, a 3-D graphics design package. In addition to the 3-D Studio models, the team translated AutoCAD models of the EBR-II for viewing in a CAVE. This model and an animation of the EBR-II refueling sequence was introduced to two operators who remarked that the CAVE would be useful to explain how the systems function to new operators and engineers. The researchers cited the virtual environment's ease of interpretation for non-technical reviewers as one of the strengths of the technology. They also remarked that the CAVE is an "excellent tool for training in developing accurate user mental models." (Brown-VanHoozer, 1996)

Working with operators for the Russian-designed RBMK reactor, researchers at Halden in Norway developed a VR simulator to train operators of RBMK reactors in refueling operations. The simulator was created from a combination of Windows and LINUX workstations. Control panels were simulated as soft panel displays, while the refueling machine and reactor hall were simulated using VRML models. (Bye, 2000)

Researchers at the University of Illinois have recently investigated methods of creating virtual reality simulations for nuclear applications. (Uddin, 2003) Their research has focused on the creation of a virtual nuclear laboratory. The multi-station laboratory includes a simulation of a sub-critical graphite pile, a virtual control room, and a simple radiation shielding demonstration. The simulations have been developed using OpenGL programming in C++. The simulations have been presented in a desktop environment with anaglyphic stereo projection. In addition, the applications have been tested in a CAVE at the University of Illinois. (Uddin, 2005) While this method of creating simulations provides some flexibility, programming can be difficult and fragile.

A collaborative project between Korea Hydro and Nuclear Power Co. and Ohio State University has been developing desktop VR applications for e-training. The researchers have created a collaborative virtual environment centered on a virtual nuclear power plant called Kodada. The virtual environment is designed to be shared over the Internet with multiple users sharing the same environment. The software includes a chat interface, which enables the users to virtually meet with distant colleagues. The virtual environment also includes a virtual a radiation environment where the avatar's (virtual human) radiation dose can be estimated and monitored. The system demonstrates a video game-like introduction to the nuclear power plant, which many can access. (Kang, 2002) (Hajek, 2004)

Researchers at Halden in Norway developed a desktop virtual reality training system to evaluate spatial familiarization methods. Groups of participants were trained using maps, guided VR where they were instructed to follow a 30 meter path connecting six points of interest, and unguided VR where participants were free to explore paths between the points of interest. In addition to transfer of route knowledge, the system was designed to evaluate radiation awareness of participants. Once the training in the VR was performed, participants entered the actual Reactor Hall and performed the measurements on the points of interest. After the experiments were completed, participants were surveyed and observed to determine radiation awareness, subjective transfer of training, subjective impression of interaction quality, and their opinion of the presence and usability of the system. Objective measures included time required to complete the task, number of measure points correctly recognized, route length, and radiation dose received.

The results of the study showed that participants were better able to locate the measurement locations after training using the two VR methods than were those who trained using the 2-D map. Additionally, the non-guided VR group outperformed the guided VR group and the map group. This result suggested the subjects who were engaged in active learning were better able to transfer what they had learned in the VR trainer to the real-world situation. The researchers note that "the training program must require active learning, which engages the learner, to fully realize the potential benefits of the technology." (Sebok, 2002)

Engineers for Iberdrola in Spain have developed four desktop virtual reality applications for nuclear power plants. CIPRES, Interactive Calculations of Radiological Protection in a Simulation Environment, dynamically calculates the dose to "workers" in a desktop virtual reality simulation. CIPRES has been applied to BWR refueling activities at the Cofrentes Nuclear Power Plant. The program shows a VR simulation of operations in a desktop virtual reality system, calculates the dose to the workers during each process simulated, and defines each activity and operator action during the simulation. "The aim of the application is to become a training tool for operators involved in refueling operations, so that both operation time and received dose could be minimized."

Another software package, TILOS (Turbine Planification for the Simulation of Turbine Dismantle), can simulate the procedures for dismantling the turbine for maintenance or changeout. The program can be used to investigate laydown spaces and component arrangements for maintenance. The software was used to study the turbine maintenance scenarios for the Cofrentes plant.

A third package, ACEWO, is a first person demonstration of the access control procedures for a nuclear power plant. The software, used as a training tool, is comprised of four modules: access to controlled areas, exit from controlled areas, ALARA, and learning about protective clothing. Each module can operate in 3 modes: an automated step-by-step mode, a stand-alone mode that prompts the user for action, and an evaluation mode that ensures the user performs operations in the correct order.

The final package, SICOMORO, is designed to optimize the man-machine interface in the design of control rooms. The software was used to help employees select new furniture for the Cofrentes plant.

The authors believe that desktop virtual reality can be directly applied to future nuclear power plants in a number of areas: Design, Decision Making, Training, Emergencies, Human Factors/HMI, and Radiological Protection. First, the technology can be used in the design of new facilities. They propose that VR can be used to improve the design of the plant before and after the plant has been built. They point out the many uses of 3D models for construction, prototyping, and documentation. Next, they believe the technology can be used to support the decision making process for optimizing procedures. The authors mention using the system to rehearse procedures, testing many different methods of performing the same activity. They believe VR can be used for training, as well. They point out three areas where VR training may be necessary: if the area is inaccessible most of the time, if the area is inaccessible due to high radiation, or if the real scenario is of high value or importance. During emergencies, VR could be used for training and to guide response teams. VR also provides a method for designing human-machine interfaces. Finally, VR may provide a means of training workers to visualize dose prior to entry into the controlled area. (Feilpe, 2003)

4 Immersive Virtual Reality Display Systems

Many universities and laboratories have access to some sort of virtual reality system, whether it's a CAVE, ImmersaDesk, Power Wall, head-mounted display, or some home-grown solution. These VR solutions provide different qualities of VR experiences, depending on many factors such as whether or not they are coupled to a tracking system, the size of display, the quality of projection, and the computing power of the image generator. The Synthetic Environment Applications Lab at the Penn State University Applied Research Lab houses a high-end VR display system called a CAVE. This system is described further in the following section.

4.1 Penn State ARL's CAVE System Components

A number of hardware components are brought together at the SEA Lab to create a high-resolution virtual environment. The SEA Lab houses a five-sided virtual reality display system, called a CAVE, which is used to generate the virtual mockup. The user views the computer-generated, three-dimensional, stereoscopic image by wearing special glasses. A mouse-like device called a Wand allows the user to easily navigate through the virtual environment. Gesture-recognizing gloves provide a means for the user to interact with the image. A motion tracking system tracks the position of the viewer's head, the mouse-like wand, and the gloves within the CAVE. These tools are described further in the sections that follow.

SEA Lab's CAVE was designed and installed by Mechdyne Corporation. The CAVE system is a turnkey virtual reality platform, which includes the display, the projectors, and all of the required hardware. A 22-processor Silicon Graphics Onyx4 computer serves as the image generator. The computer uses 10 separate graphics processors that render each eye for the five screens. The left eye and right eye images are interlaced using an external box called a compositor. A High-Bandwidth BarcoGraphics CRT projector projects the image generated by the computer on to a Mylar mirror, which reflects the image onto the back of each of the four wall screens. Penn State ARL has custom built CAVE system with four walls that surround the user as well as a top-projected floor. A diagram of the Penn State ARL CAVE is shown in Figure 1.

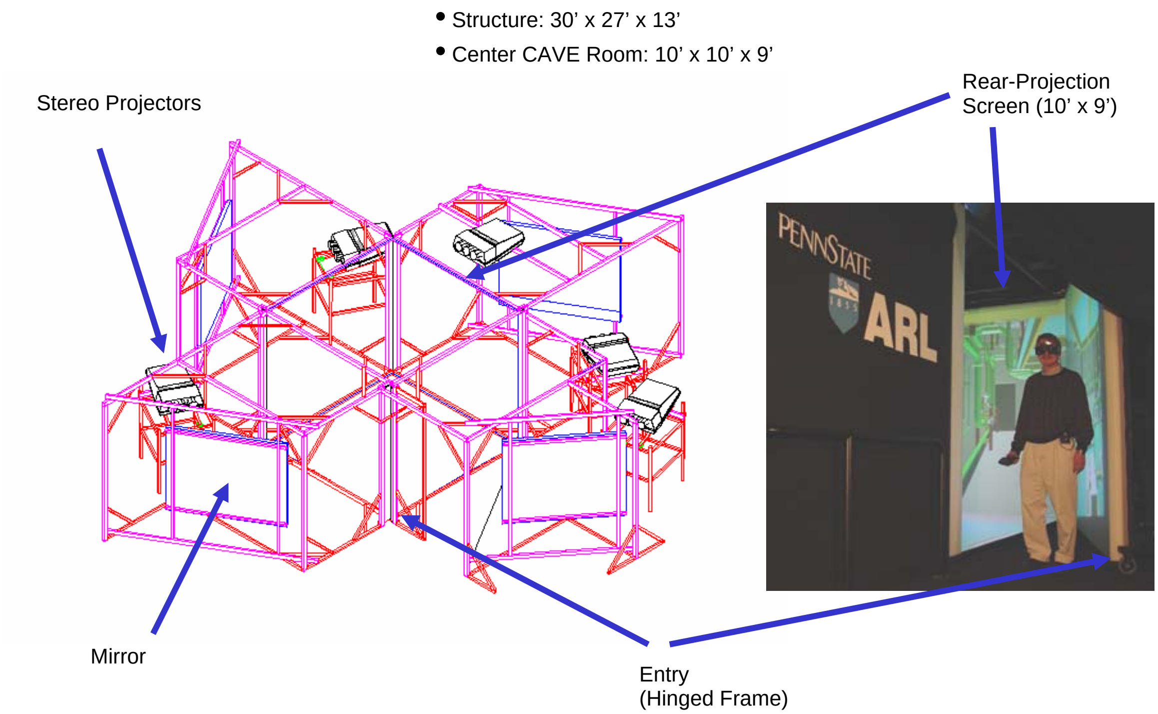


Figure 1: PSU ARL Immersive Projection Display System

The CAVE creates a three-dimensional stereoscopic image using a technique called active stereo. In order to create the stereo image, the computer generates 96 frames of information per second. Forty-eight are optimized for viewing in the right eye, and 48 are optimized for viewing in the left eye. StereoGraphics CrystalEyes glasses, worn by the user, have LCD shutters in the lenses. The glasses receive IR signal from emitters at the top of each wall, which synchronize the shutters to the image being projected. When the left eye image is being projected on the screen, the right lens of the glasses is blacked out. When the right eye image is being projected, the left lens is blacked out. The switching of the images is imperceptible to the user. Active stereo provides a high quality stereoscopic image, although the projection of the image in stereo causes the image to appear dimmer than the typical monoscopic image. The glasses and wireless tracking sensor are shown in Figure 2.

Figure 2: Active Stereo LCD Shutter Glasses

A number of tools are combined to develop intuitive interaction with the virtual mockup. The motion tracking system and the Wand are described below.

The SEA Lab's CAVE utilizes an Intersense IS-900 VET motion tracking system. The wireless tracking system tracks the user's position and orientation using a system of ultrasonic transmitters and microphones. The system provides real-time position data, including X,Y,Z position and orientation angles. Currently, the SEA Lab system uses 2 wireless sensors: one on the Wand and one on the glasses. The system is capable of tracking 4 sensors, allowing for future expansion of this capability.

To navigate through the virtual mockup, a commercially available, specialized 3-D joystick called the MiniTrax Wand is used. The Wand has a multidirectional joystick, which allows the user to control movement in the virtual environment. In addition, it has five programmable buttons, which may be assigned to different activities in the mockup. The Wand is shown in Figure 3.

Figure 3: MiniTrax Wand

5 Creating Full-Scale Virtual Mockups

The hardware described in the previous section can be used to create full-scale virtual environments that can be freely navigated and investigated. Interfacing with this technology enables developers to create realistic and believable experiences for those immersed in the environment.

5.1 Why Create A Virtual Mockup?

Once created, these mockups have many potential uses including design review, familiarization training, and construction review and planning. In the past, scale plastic models were built by designers to lay out systems and communicate designs to customers. Presently, designers create three-dimensional product models to perform those tasks.

Each of these methods has drawbacks, however. Scale models are expensive to create and the small scale often doesn't show sufficient detail to be useful for anything more than general orientation. For example, the scale model of AP600, shown below on the left, is estimated to have cost approximately $600,000. Full-scale physical mockups can be constructed, as well, although they are expensive to build and must be maintained and stored. Three-dimensional CAD product models and walkthrough CAD systems are a great improvement over the scale plastic models, previously used, although they have weaknesses of their own. While the technology exists to present this data in stereo on a desktop computer or even a large format display, it often fails to communicate an accurate sense of scale to the user.

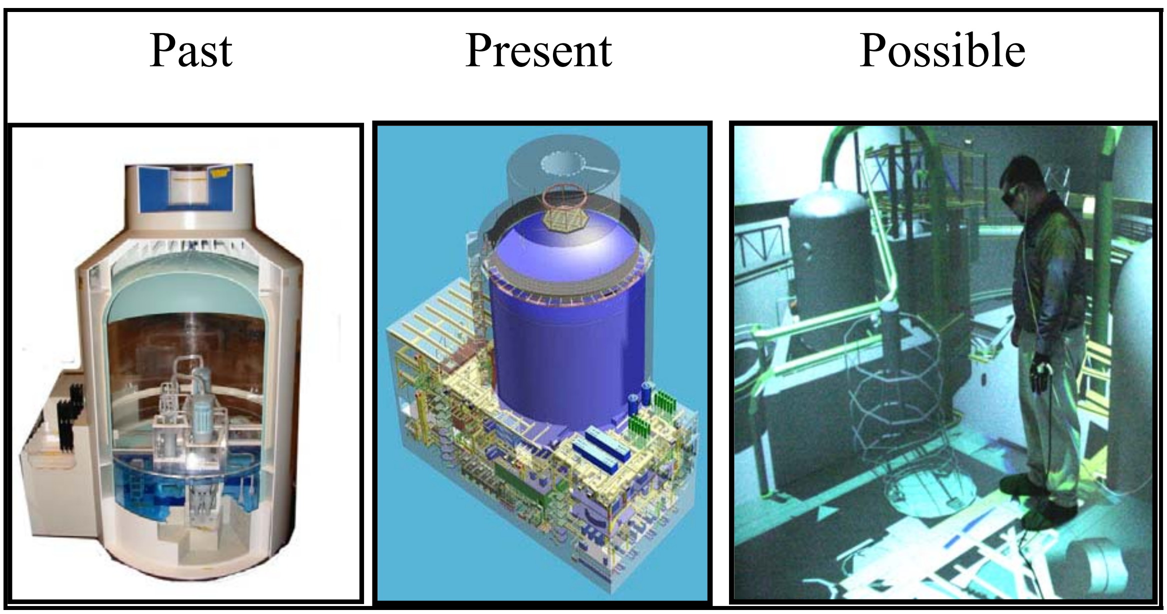


Figure 4: Design Review: Past, Present, Future? (l to r)

Full-scale virtual mockups have a number of advantages and one significant drawback. These mockups, presented in a CAVE display system, are freely and easily navigated. The virtual mockups created for this project utilize a "point-and-go" model in which the user need only to point in the direction he wishes to travel and push forward on the joystick on the wand to navigate the mockup. The user has the option of clamping to the ground with simulated gravity or flying around, gaining a different perspective. In addition to intuitive navigation, the virtual mockup provides the user with a full-scale, one-to-one, representation of the geometry. Actually being immersed in the space gives the user a truer sense of scale than that provided by a desktop display. Displaying the data in a stereoscopic environment provides the user with an accurate sense of depth and relative size of equipment. There is, however, one drawback to this technology. It is expensive. A CAVE system similar to the one at Penn State ARL's SEA Lab can cost nearly two million dollars, although multiple mockups can be created and displayed on the system.

5.2 Creating Full-scale Virtual Mockups from CAD Models

Full-scale virtual mockups can be created directly from the output of many standard three-dimensional CAD software packages. Many export formats are available from these packages, which may then be imported for viewing in a CAVE display system. The models created using a 3-D CAD package are exported into one of the file formats that the CAVE rendering software will recognize. Among the file formats tested over the course of this project were Virtual Reality Modeling Language (VRML), Silicon Graphics' Open Inventor, and Multigen-Paradigm's Open Flight. Specialized software tools enable the user to translate and manipulate each of these formats.

Most of the mockups discussed in this report were created by translating the CAD models into VRML format using the export feature of the CAD software. From the VRML format, the files were translated into SGI's Open Inventor format, which requires a few small changes to the VRML file including changing the header, reordering the vertices, and removing the pre-programmed viewpoints. Open Inventor is a superset of the VRML standard. Open Inventor format may be read directly by the CAVE's rendering software or one additional translation can be made to create a Performer Fast Binary (PFB). Multigen-Paradigm's Performer controls the rendering of the scenes in the CAVE display, and the Performer binary is the preferred file input to that program. The translation to Performer binary decreases the load time for the models since the system will convert any input file into a Performer binary during the load process if it has not been converted already. The Explorer program, based on Multigen-Paradigm's Vega application programming interface (API), controls the interaction between the user and the surrounding environment. The process used to create the virtual mockups detailed in this report is shown in Figure 5.

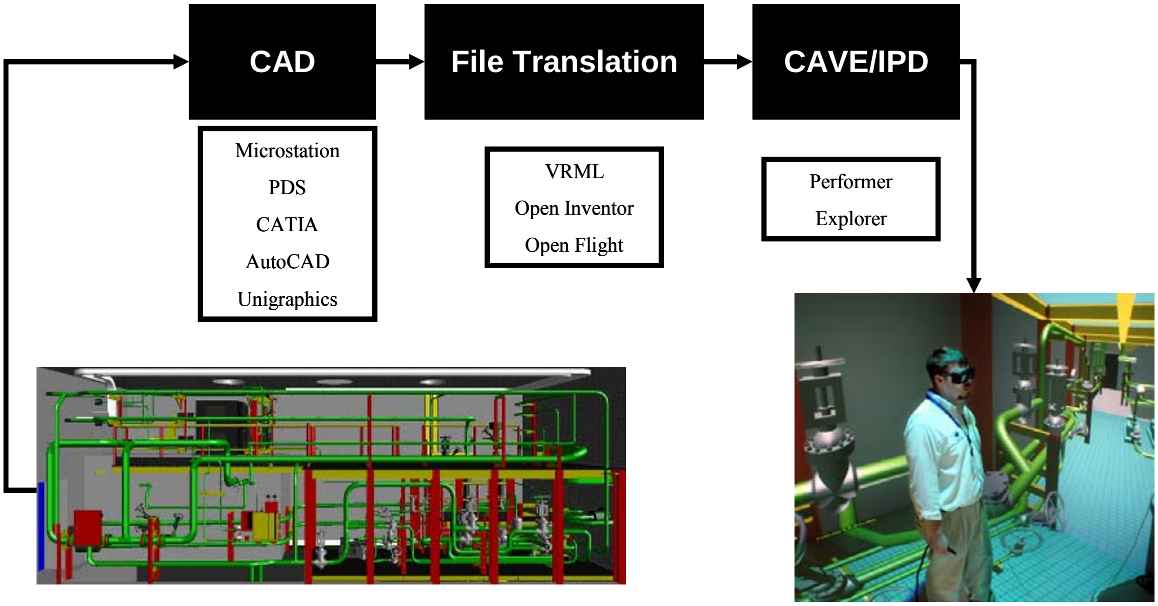


Figure 5: Creating Full-scale Virtual Mockups from CAD Models

6 Observation of Nuclear Power Plant Training Activities

The training activities of three utilities were observed in order to determine the types of tasks training programs cover, while the training activities of a fourth utility were discussed with one of its training personnel.

6.1 Limerick Generating Station

On 29 September 2003, Vaughn Whisker traveled to Limerick Twp, PA to visit Exelon Nuclear's Limerick Generating Station. He met with Bob Warren, a member of the training group at Limerick. After Vaughn presented a recap of the NERI research project, Bob discussed some of the methods used for Radiation Worker Training, Advanced Radiation Worker Training, and General Employee Training. Bob provided Vaughn with a number of helpful training materials that cover the training of supplemental radiation protection (RP) personnel, a format used for development of dynamic learning activities (discussed later), a representative procedure used for on-the-job training (OJT) or Task Performance Evaluation (TPE), and an example of a retraining/reinforcement procedure for radiation protection personnel. These documents will be used to guide the development of the experiments for Task 4.

The Teletrix system is a radiation meter simulation system. The components of the Teletrix system are shown in Figure 6. Special survey meters respond to an artificial count rate set by a transmitter. The instructor turns the dials on the transmitter and the appropriate reading is displayed by the survey meter. A number of form factors are available. More information on the system can be found at www.teletrix.com.

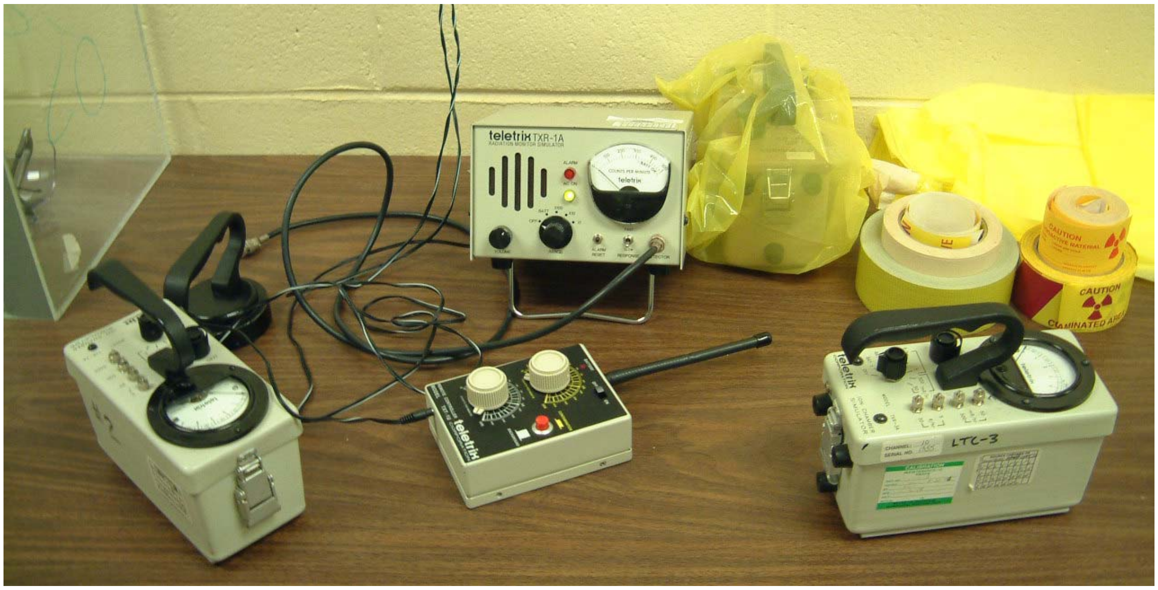


Figure 6: Teletrix Radiation Meter Simulators

In addition to the Teletrix system, the training lab also had a physical mockup of a static pipe loop. The loop is used to demonstrate the basic procedures of surveying and breaching closed systems. The test stand was procured from GPU when Exelon bought TMI. The loop was due to be scrapped. While it could formerly be filled with water, the system appears to have been dry for some time. The loop is comprised of piping of various diameters from 6-inches to 1-inch in addition to a motor-operated valve, a gate valve, a flange, a water supply tank, a small pump, and numerous sample lines. This small, simple test stand may be used as a possible physical mockup-VR mockup benchmark. The loop is shown in Figure 7.

Figure 7: Static Training Test Stand

Mr. Warren noted that Limerick has mothballed most of their mockups while they wait for a new training building to be constructed. He said that much of the job training is based on classroom review and pairing experienced personnel with inexperienced personnel. Task review during the ALARA prejob briefing is now the norm. Personnel will typically walkdown the work area sometime prior to the job being performed. The ALARA briefing and walkdown will often specifically point out hold points in the procedure where radiation protection technicians or personnel are to be involved in order to limit unnecessary radiation exposure.

Mr. Warren discussed some of the other training activities his group performs. One of the ways they reinforce classroom learning is through dynamic learning activities (DLA). These activities are designed to improve the knowledge and skills of advanced radiation workers and to decrease the likelihood of a "human performance related event." The DLA are scenario-based training exercises built around simulated activities. The scenarios are often based on events that have occurred at other plants in order to prevent similar occurrences at Limerick.

The Advanced RWT program trains certified radiation workers to perform limited surveys of their work areas in order to reduce the workload on radiation protection personnel during outages. There are limits on the amount or contamination or radiation that can be present in a work area surveyed by the ARW. The ARW must pass additional training programs to be certified. An ARW training scenario could be developed using the virtual mockup.

After the presentation and discussion, Mr. Warren's impression of the full-scale virtual mockup technology was that it would best be used in dynamic learning activities because of its flexibility. In addition, he noted that the most "bang for the buck" would be achieved in training for very high dose operations. One such operation that was also mentioned by PPL is control rod drive maintenance. Some other activities he discussed were mainly dose significant tasks that occur fairly often including:

- Most activities occurring in the Drywell, containment, refueling floor
- Undervessel control rod drive maintenance
- Control rod drive disassembly
- Recirculation pump maintenance
- Main Steam Isolation Valve (MSIV) maintenance

Another interesting development that Mr. Warren noted was the use of real-time dose monitoring. The Siemens electronic dosimeter, shown in Figure 8, in use at Limerick has the capability to send dose information to a computer network in real time. Radiation protection personnel can observe the dose information from an activity remotely. This may be a capability that could be simulated with the VR dose model.

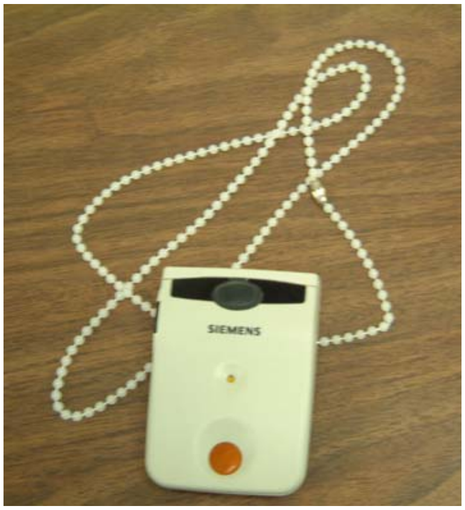


Figure 8: Siemens EPD-2 Dosimeter

6.2 Susquehanna Steam Electric Station

The Susquehanna Steam Electric Station has two facilities that house mockups for training. The Learning Center houses a number of mockups, and the West Building houses the Performance Simulator.

The control room simulator and classrooms are housed in the Learning Center. Classroom training for chemistry, electrical, and mechanical specialties is also held at the Learning Center. A full scale mockup of the area under the vessel is used for control rod drive maintenance training.

Outside of the learning center are a small building that houses the closed cooling water (CCW) mockup and the valve trailer. The CCW mockup, shown in Figure 9, is a large skid with multiple pumps, a heat exchanger, and many valves. The mockup is used for training personnel in electrical maintenance, valve maintenance, and proper work procedures. The valve trailer contains many of the valves that are used in the plant. It is a hands-on training facility where the valves can be assembled and dis-assembled.

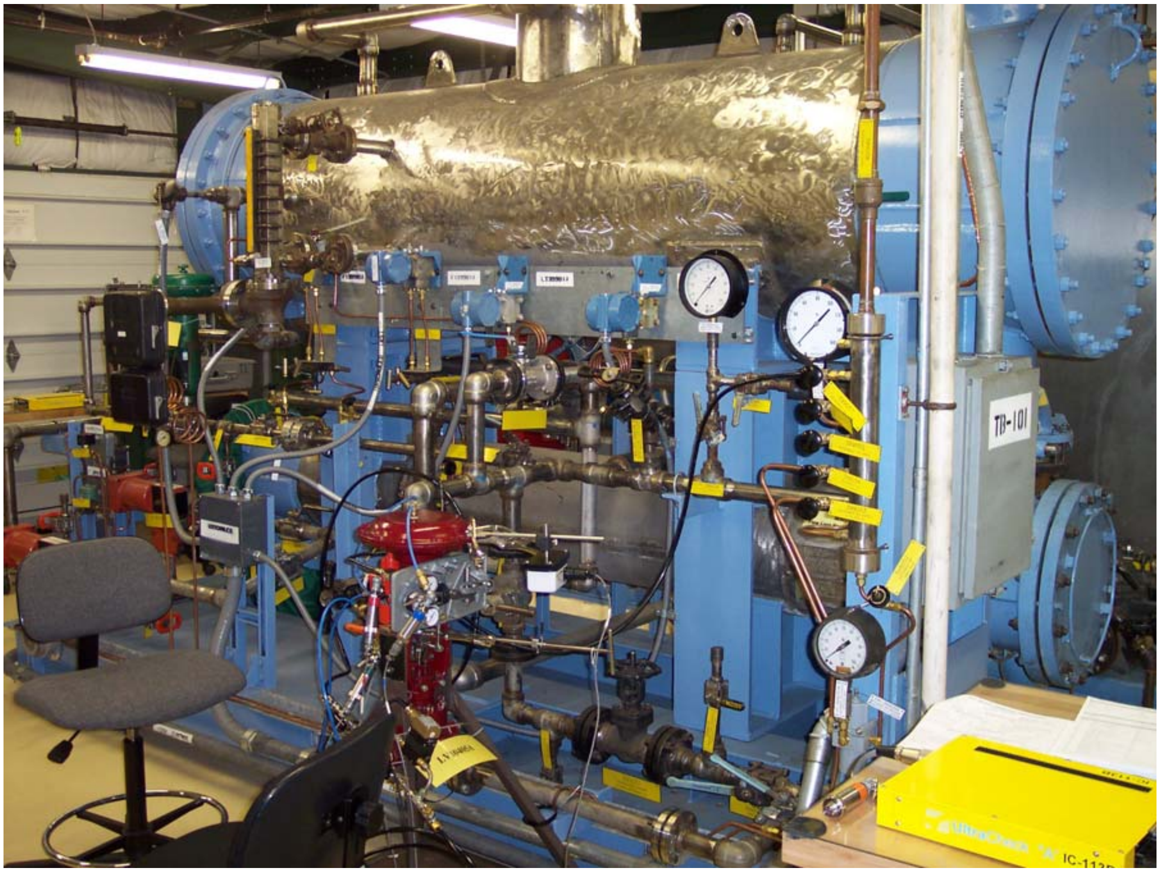


Figure 9: SSES CCW Physical Mockup

The second facility housing physical mockups is the Performance Simulator. The Performance Simulator is a multi-station training facility. When completed, it will be a 12 station hands-on learning laboratory. Currently, the Performance Simulator has only three stations. The three stations constructed to-date are used to train employees in electrical panel maintenance, ALARA and procedure reading, and housekeeping. Two of these stations are shown in Figure 10.

Figure 10: SSES Performance Simulator Stations

The Performance Simulator stations are designed for role playing exercises. The personnel involved in these exercises are encouraged to view the activities as practice rather than training. In the role-playing exercises, two groups generally participate – one group performs the task while the second group observes and coaches. The environment is designed to encourage team members to speak up, to stop at critical points, and to correct incorrect behavior. The two teams are asked to keep in mind four key questions as they perform the activity:

- What are the critical steps or phases of this task?
- How can we make a mistake at that point?
- What is the worst thing that can go wrong?
- What barriers or defenses are needed?

The activities are designed to reinforce many work practices including peer checking, STAR, proper 3-way communication, procedure use, evolution termination criteria, and discussions of operating experience.

6.3 Perry Nuclear Power Plant

The Perry Nuclear Power plant's training program has been featured in a number of publications including the Nuclear Professional and Nuclear News (McCullough, 2004). A member of the project team visited the Perry Nuclear Power Plant to meet with their nuclear training personnel to tour their mockups.

Like all nuclear power plants, Perry has a full scale physical replica simulator for the control room. The control room for the BWR is laid out in a more "wrap-around" fashion. After a discussion of the current capabilities of the CAVE VR display, Jim Beavers, an operations training instructor, said that a virtual model of the control room would not be helpful due to the fact that many operators rely on their sense of touch. He demonstrated this by role playing the "typical operator." He held the binder of procedures in one hand, had one hand on the controls, and had a pencil in his mouth. It is unclear how the CAVE could be used to mimic this situation with no haptics or force feedback. Mr. Beavers mentioned that while a replica of the control room may not be beneficial, a mockup of the local diesel generator control panel or some of the back panels and/or electrical cabinets might be helpful for operator training.

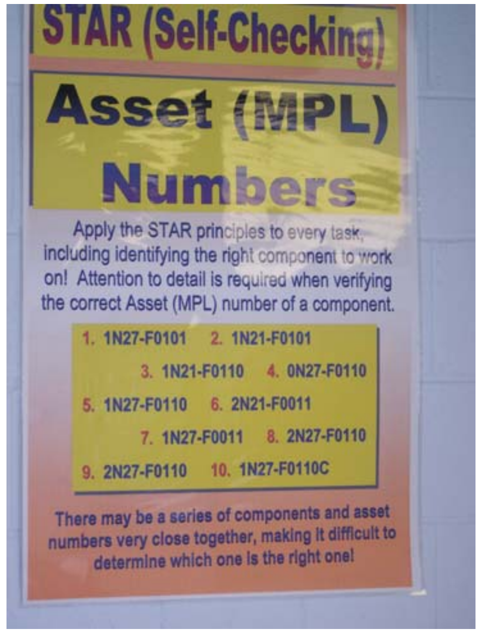
Mr. Beavers demonstrated a desktop operator training system they use when the simulator is not available. The program was built using ActiveX controls. The simulation showed photo-realistic representations of panels in the control room. Clicking on a switch would open a dialog box with all of the "options" for operating that switch. The dialog box includes some logic that locks out certain actions before others happen. For example, a lube oil pump must be switched on before operating one of the diesel generators. Mr. Beavers noted that the development of the system was difficult because of the constant back-and-forth with the software engineers who, in his opinion, had no inside knowledge of what the end user would want/need. This example demonstrates the need for an engineer with knowledge of the system to be involved in the development of these simulators.

Perry has a large fire brigade training facility. The facility has a large tower used for ascending and descending training, a burn building, a tank to simulate gas fires, a transformer to simulate transformer fires, and 3 trailers connected used for SCBA training. The SCBA facility is a training "maze," a system of obstacles designed to give trainees an idea of how to navigate confined spaces with their breathing apparatus. This is another facility that relies heavily on the sense of touch and feeling, and therefore, would not lend itself to re-creation in VR.

The maintenance training facility known as the "Loop of Excellence" contains a number of mockups. Some of these are related to the large flow loop, while others are simply small mockups of areas of interest. These smaller mockups include the control rod drives and the reactor water cleanup pump room. The flow loop mockup area includes two skids taken from the never-completed unit 2 plant, and it has a control room and electrical panels. When the mockup is used for training, a dose map of the area is given to the trainees. The dose map contains simulated radiation "measurements" at a number of locations. While the trainees typically wear protective clothing and dosimetry, the equipment is basically for show, providing no valuable feedback on radiation exposure or contamination. The mockups appear to be a significant part of their training program.

Figure 11: Training Mockups from Perry Nuclear Power Plant

The Error Lab is a collection of mockups and displays that are used to illustrate common errors in work practices. It was comprised of generally static displays on rigging techniques, procedures for reading equipment labels, storage of chemicals in cabinets, storage of liquids in drums, storage of flammable materials, working at heights and rigging scaffolding, working with electrical systems, proper use of personal protective equipment (PPE), and foreign material exclusion (FME) programs.



Perry also use a mockup to train people on the procedures for dressing out and accessing the protected area. They have a mockup of the RP desk, a book of RWPs and dose maps, the dosimeter/RWP login, the turnstiles, a few piping systems with dressed out mannequins to demonstrate work practices, a step-off pad, a PCM (Personal Contamination Monitor), a SAM (Small Article Monitor), and an exit turnstile. These mockups were used for access training and radiation worker training.

The final demonstration was of their desktop VR system they use for training/requalification on the procedures for dressing out and accessing the protected area – selecting an electronic dosimeter, logging in on an RWP, donning and removing protective clothing, etc. The system is windows-based, a combination of pictures and digital video. The videos illustrate common mistakes as well as proper procedures.

6.4 San Onofre Nuclear Generating Station

Robert Sandstrom from San Onofre discussed his utility's activities, which use physical mockups. Mr. Sandstrom described their use of mockups for survey training, decontamination, plant entrance and exit, introduction to plant rules, and the proper use of tools. Since steam generator maintenance is a high dose-activity, a mockup of the steam generator manway is used to train workers to perform nozzle jumping activities. Mockups are also used to train personnel on the proper use of robotic tools. SONGS also uses a mockup to train workers in performing electrical breaker maintenance. Finally, they train personnel to improve human performance such as the STAR principle and proper reading of procedures.

Mr. Sandstrom recommended creating mockups for other activities including changing filters in letdown system because they are heavy, radioactive, and hard to access. In addition, other high dose activities such as maintaining the pump seals on the reactor coolant pump. Finally, he recommended a mockup of the head area to train workers for inspection tasks.

7 Use of Mockups for NPP Training Activities

The changing training environment and two additional examples of the successful use of physical mockups or models are described below.

7.1 Improving Performance using Mockup Training

An article written by Philip McCullough, Executive Director of the National Academy of Nuclear Training (NANT), highlights the link between training and improved plant performance. McCullough highlights the mockup training at Perry, describing the flow loop simulator that duplicates four closed-loop systems – cleanup, cooling, heating, and recirculation. Perry uses the simulator as a problem solving tool, a rig to test new methods, and a place to develop improvements that lead to advances in plant performance. The simulator is also used to practice pre-job briefings and achieve error-free modifications to the plant. McCullough notes that the training environment is changing to so that success is defined with an overall goal and the training that occurs is designed to meet that goal. The goal could be something like a 20-percent reduction in personnel dose or an error-free maintenance evolution. The new training environment also makes use of different measures of effectiveness than the old one does. The new methods focus on transfer of knowledge to the learner, the learner's performance improvement, and the ultimate impact on the business. (McCullough, 2004)

7.2 North Anna Steam Generator Replacement

The steam generator replacement project at North Anna Unit 1 in the mid-1990's made significant use of a physical mockup to plan the work and to reduce radiation exposure to workers. Steam generator replacement is a complex labor-intensive and exposureintensive undertaking. The mockup training program was used to address the ALARA principles of minimizing time, maximizing distance, and optimizing shielding in order to reduce radiation exposure.

The activities that would be trained on the physical mockup were carefully evaluated based on the following criteria:

- Time required to perform task
- Physical location of the task
- Complexity of the method used to perform the task
- Contact and general area dose rates
- Experience with technology used to perform the task

Based on these criteria, the following tasks were selected for mockup training:

- Installation of temporary reactor coolant piping supports
- Mechanical cutting of reactor coolant piping
- Removal of old steam generator support blocks
- Dry blast decontamination of the reactor coolant pipe ends
- Installation and removal of shielding
- Installation and removal of debris dams in the reactor coolant piping
- Machining of the reactor coolant piping
- Rigging of reactor coolant elbows
- Weld build-up of the reactor coolant piping
- Setting and alignment of the new steam generator on the lower support structure
- Welding of the steam dome to the lower assembly
- Reactor coolant pipe and steam dome internal radiography setup
- Primary system foreign object search and retrieval
- Operation of lower assembly transport carriage
- Tube bundle/annulus protection removal
- Optical templating of the steam generator channel head and reactor coolant piping

A 40’x 40’ x 30’ building housed the physical mockup. The mockup consisted of a full-scale steam generator channel head and lower support structure. A full scale mockup of the transition cone was manufactured and installed on the mockup. In order to simulate the operational and environmental constraints, scaffolding and shielding were erected around the mockup. Personnel wore the appropriate protective clothing and operated under the expected environmental conditions such as elevated temperature. Activities that were selected for the mockup training were performed twice on the mockup prior to their performance in the field.

The authors provide a list of lessons learned from the mockup training activities:

- The program should be developed jointly between the utility and the contractor so all affected organizations are part of the process

- Continuity between the workers and their radiation protection team should be maintained. The radiation technicians that work with the personnel on the mockup should be the same ones they will work with in the field.
- Mockup training should occur as close to the actual task performance as possible to prevent workforce attrition.
- The better the mockups recreate the work environment; the better prepared the workers that train on the mockups will be for their real-world task.

The mockup resulted in a significant reduction in personnel radiation exposure during the maintenance activity. The original exposure estimate was 480.7 Person-REM. The actual exposure received during the steam generator replacement was 239.9 Person-REM. In addition, use of the mockup prior to completion of the actual activity determined that commonly used tools could not be used due to the unique configuration of the support structure. This would have severely impacted the schedule had it been discovered in the field rather than on the mockup. (Henry, 1996)

7.3 Calvert Cliffs Steam Generator Replacement

The Calvert Cliffs nuclear power plant underwent a steam generator replacement on its second unit in 2003. The staff at Calvert Cliffs used detailed 1/16 scale models to prepare for the activity. The models were used to determine the requirements for removal of equipment. It gave the engineers planning the job an idea of how components might interfere with each other during removal and installation activities. The cost of creating the model is estimated to have paid for itself in the planning improvements, although there is "no easy correlation of direct [cost] savings associated with the training use of the model." (Baines, 2003)

8 Radiation Dose Model Development:

In order to facilitate the use of immersive virtual reality technology as a training and procedure development tool, a radiation dose model was created. The dose model is designed to allow workers' radiation exposures to be tracked for any selected activity while they perform simulated maintenance activities in the immersive virtual environment. Using the conventional dose equations, the radiation field due to a point source can be modeled. The program used to calculate this radiation dose is described in the following sections.

8.1 Input:

The input to the dose model is currently read from a configuration file that is loaded at the same time as the geometry. This is the same file that can be used to program and view installation sequences. The configuration file contains a few lines for each source. The source strength in Becquerels, the energy of the emitted photons in MeV, and the x,y,z position of the source are read from a block in the file. This information is stored in an array for later use. The array sizes are currently allocated to store information for 10 sources; however, this choice was arbitrary and can be changed at any time. A sample radSource input is shown in Table 1 below:

Table 1: Input for Radiation Dose Model

```
radSource "source1" {
pos 143.0 124.0 -0.02;  → x,y,z position of source
energy 1.33;                  → Photon energy in MeV
strength 3.7e7;         → source strength in Bq
}
```

8.2 Calculation Procedure:

The dose calculation program is a FORTRAN subroutine that may be called from FORTRAN or C++. The routine makes use of three FORTRAN function subroutines to calculate the mass attenuation coefficient in air, the mass-energy absorption coefficient in air, and the mass-energy absorption coefficient in tissue.

The position of the observer is passed into the program, and the total dose rate to the observer at that position is returned. The program reads source information from the configuration file, described in section 8.1. The configuration file contains blocks of code that set the source strength in Becquerels, the energy of the photons being emitted by the source, and the source position. Next, the program calculates the distance between the observer's position and the source. Then, the function subroutines are called to calculate the attenuation and mass-absorption coefficients for use in the flux calculation, the exposure calculation, and the dose calculation. Next, the program calculates the flux using the distance, the source strength, and the attenuation coefficient for air. The exposure rate is calculated by multiplying the flux by the energy and the mass absorption coefficient in air. Exposure rate is then converted to dose rate. The dose rate for each source is stored, and the total dose rate is determined by adding each source's contribution. The resulting value is passed back to the shell program, where it is used when the dose model is active within the environment. This calculation sequence is depicted in Figure 12.

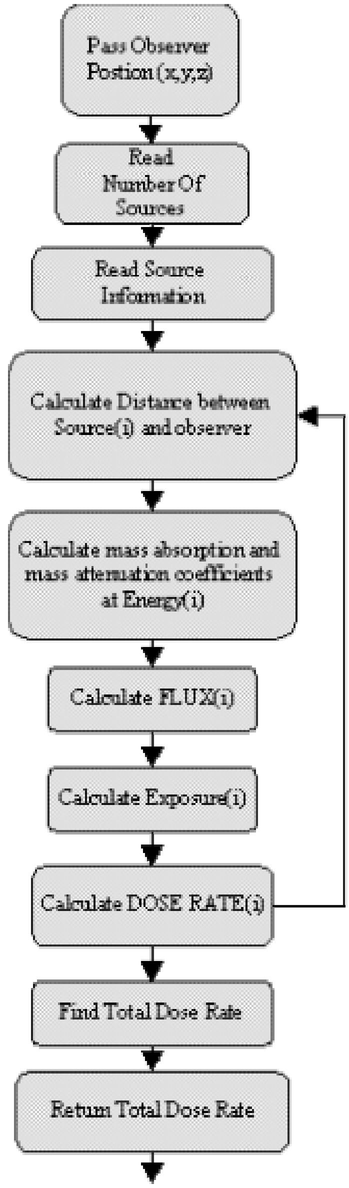


Figure 12: Flow of Dose Calculation Program

8.2.1.1 Flux Calculation

The flux from a point source is inversely proportional to the distance between the source and the observer squared. An attenuation term is appended to the point source formula to give a more accurate representation of the actual flux at point r, although, in most cases, the attenuation caused by air is very small. Equation 1 shows the equation for the flux at point r.

$$\varphi(r) = \frac{S}{4\pi r^2} * e^{-\mu_{air} r} \quad (1)$$

where:

S = source strength in Becquerels (dps or tps)

r = distance from source in centimeters
μ = attenuation coefficient in material (cm^{-1})

8.2.1.2 Exposure Rate Calculation

The exposure due to the photon flux can be calculated by multiplying the flux by the energy of the photon and the mass-energy absorption coefficient. The leading coefficient represents the combination of a number of unit conversion factors, which are used to calculate the exposure in units of milliRoentgen per hour.

$$\dot{X}\left[\frac{mR}{hr}\right] = 0.0657 * \varphi_{\gamma} * E * \left(\frac{\mu}{\rho}\right)_{air} \qquad (2)$$

where:
ϕ = flux in photons/cm^2-s
E = Energy in MeV
$\left(\frac{\mu}{\rho}\right)$ = mass absorption coefficient in cm^2-g

8.2.1.3 Dose Rate Calculation

Once the exposure at point r has been calculated, the whole-body dose to the tissue can be calculated by multiplying the exposure by the ratio of the mass-energy absorption coefficients in tissue to the mass-energy absorption coefficient in air, shown in Equation 3. The coefficient represents the unit conversion from Roentgens to rads.

$$\dot{D}\left[\frac{mrad}{hr}\right] = 0.875 \frac{\left(\frac{\mu}{\rho}\right)_{tissue}}{\left(\frac{\mu}{\rho}\right)_{air}} * \dot{X} \qquad (3)$$

The effective dose or dose equivalent in rem is obtained by multiplying the dose in rads by a quality factor that accounts for the different linear energy transfer of the various types of radiation. The quality factor for photons is 1; therefore, the absorbed dose and dose-equivalent are numerically equal.

8.2.1.4 Description of Unit Conversions and Coefficients

The leading coefficient in the calculation of exposure rate is the result of the conversion from flux to exposure.

$$\dot{X}\left[\frac{R}{hr}\right]=\frac{\phi\left[\frac{photons}{cm^2-s}\right]*E\left[\frac{MeV}{photon}\right]*1.602x10^{-13}\left[\frac{J}{MeV}\right]*3600\left[\frac{s}{hr}\right]*\left(\frac{\mu}{\rho}\right)\left[\frac{cm^2}{g}\right]*\frac{1000g}{1kg}*3881\frac{R}{\frac{C}{kg}}}{34\frac{\frac{J}{kg}}{\frac{C}{kg}}}$$

$$\dot{X}\left[\frac{R}{hr}\right]=6.57x10^{-5}*\phi\left[\frac{photons}{cm^2-s}\right]*E\left[\frac{MeV}{photon}\right]*\left(\frac{\mu}{\rho}\right)$$

$$\dot{X}\left[\frac{mR}{hr}\right]=0.0657*\phi\left[\frac{photons}{cm^2-s}\right]*E\left[\frac{MeV}{photon}\right]*\left(\frac{\mu}{\rho}\right)$$

The leading coefficient in the exposure-dose conversion is a result of the unit conversion between rad and Roentgen. The different amount of energy that must be deposited in each material (air and tissue) to liberate the $2.58x10^{-4}$ Coulombs of charge results in the conversion factor.

$$1\,\text{rad}=\frac{100\,erg}{g\,(tissue)}*\frac{1MeV}{1.60x10^{-6}erg}=6.25x10^{7}\,MeV/g$$

$$1R=\frac{2.58x10^{-4}C}{1kg}*\frac{1\,\text{ion pair}}{1.602x10^{-19}C}*\frac{34\,eV}{1\ \text{ion pair (in air)}}=5.476x10^{16}\frac{eV}{kg}=5.47x10^{7}\frac{MeV}{g}$$

$$1R=5.47x10^{7}\frac{MeV}{g}*1.60x10^{-6}\frac{erg}{MeV}=87.5\frac{erg}{g\,(air)}$$

$$1\,\text{rad}=\frac{5.47\text{x}10^{7}\,\frac{MeV}{g\ air}}{6.25x10^{7}\,\frac{MeV}{g\ \text{tissue}}}*\frac{\left(\frac{\mu}{\rho}\right)_{tissue}}{\left(\frac{\mu}{\rho}\right)_{air}}*1R=0.875\left[\frac{\left(\frac{\mu}{\rho}\right)_{tissue}}{\left(\frac{\mu}{\rho}\right)_{air}}\right]*1R$$

8.2.1.5 Calculation of Energy Dependent Constants

In order to facilitate their use in the dose-modeling program, polynomial fits of NBS (now NIST) data for the attenuation coefficient and mass absorption coefficient were created to reduce the error resulting from the assumption of a single value. The polynomial fits for the mass-absorption coefficients were divided into two segments to reduce the error. It is important to use additional significant figures when programming polynomial fits to data. Failure to do so can result in large errors.

8.2.1.5.1 Calculation of the Mass-Energy Absorption Coefficient for Air

The energy-dependent mass absorption coefficient for air was fit using two segments: one segment covers the range from 100 keV to 2 MeV, while the other segment covers the range from 2 MeV to 10 MeV. The expression used for the first segment between 100 keV and 2 MeV is:

$$\mu_{air} = -5.352911\text{x}10^{-3}*E^6 + 4.070676\text{x}10^{-2}*E^5 - 1.249188\text{x}10^{-1}*E^4 + 1.989121\text{x}10^{-1}*E^3 - 1.744636\text{x}10^{-1}*E^2 + 7.592420\text{x}10^{-2}*E + 1.718055\text{x}10^{-2} \quad (4)$$

Over the range of 100 keV to 2 MeV, the error associated with the use of the functional fit is less than 1 percent.

The expression for the second segment between 2 and 10 MeV is:

$$\mu_{air} = 2.774191\text{x}10^{-6}*E^4 - 8.508536\text{x}10^{-5}*E^3 + 1.033186\text{x}10^{-3}*E^2 - 6.370574\text{x}10^{-3}*E + 3.303224\text{x}10^{-2} \quad (5)$$

Over the second segment, covering 2 to 10 MeV, the error associated with the use of the functional fit is, again, less than one percent. Figure 13 shows the measured NBS mass-energy absorption coefficient and the function fit to that data used in the dose model calculation.

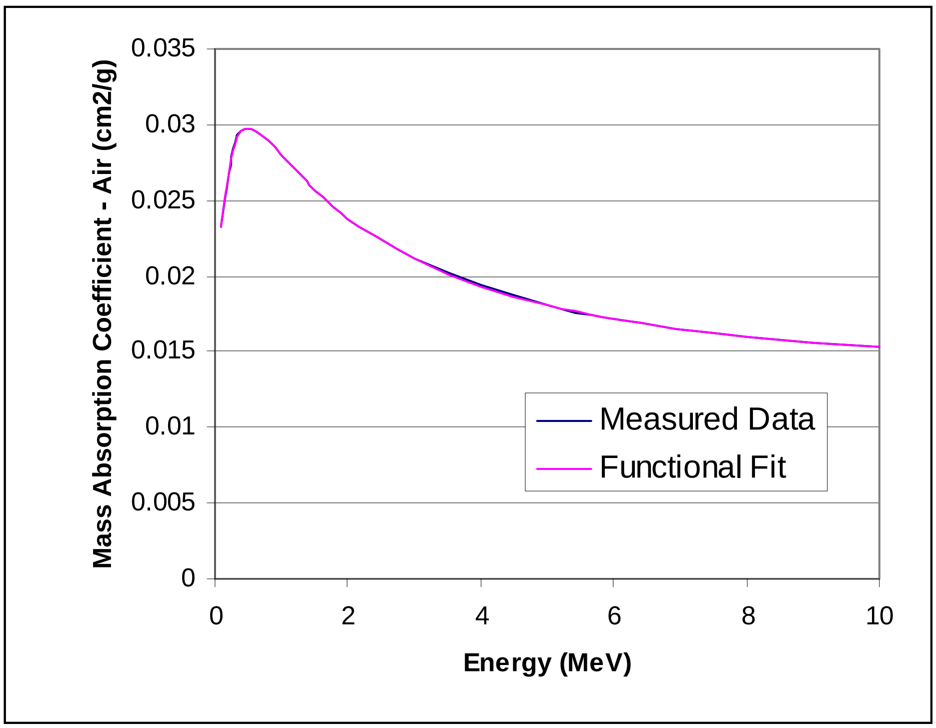


Figure 13: Comparison of Measured and Calculated Mass-Energy Absorption Coefficient for Air

8.2.1.5.2 Calculation of the Mass-Energy Absorption Coefficient in Tissue

The mass-absorption coefficient for tissue was fit using two regions, as well. The first region, again, covers the area between 100 keV and 2 MeV. The second region covers the area between 2 MeV and 10 MeV. The expression for the coefficient covering the first region is:

$\mu_{tissue} = 4.251514x10^{-3}*E^6 - 2.094159x10^{-2}*E^5 + 2.935603x10^{-02}*E^4 + 8.518912x10^{-03}*E^3 - 5.411368x10^{-2}*E^2 + 3.931925x10^{-2}*E + 2.360246x10^{-2}$ (6)

The use of this equation results in an error of less than four percent compared to tabulated data.

The expression for the second region is:

$\mu_{tissue} = 8.38606x10^{-6}*E^4 - 2.25563x10^{-4}*E^3 + 2.26668x10^{-3}*E^2 - 1.08867x10^{-2}*E + 3.99109x10^{-2}$ (7)

The use of this function results in errors of 1-percent or less for the entire energy range. Figure 14 shows a plot of the NBS data and the functional fit of the data used in the dose modeling program.

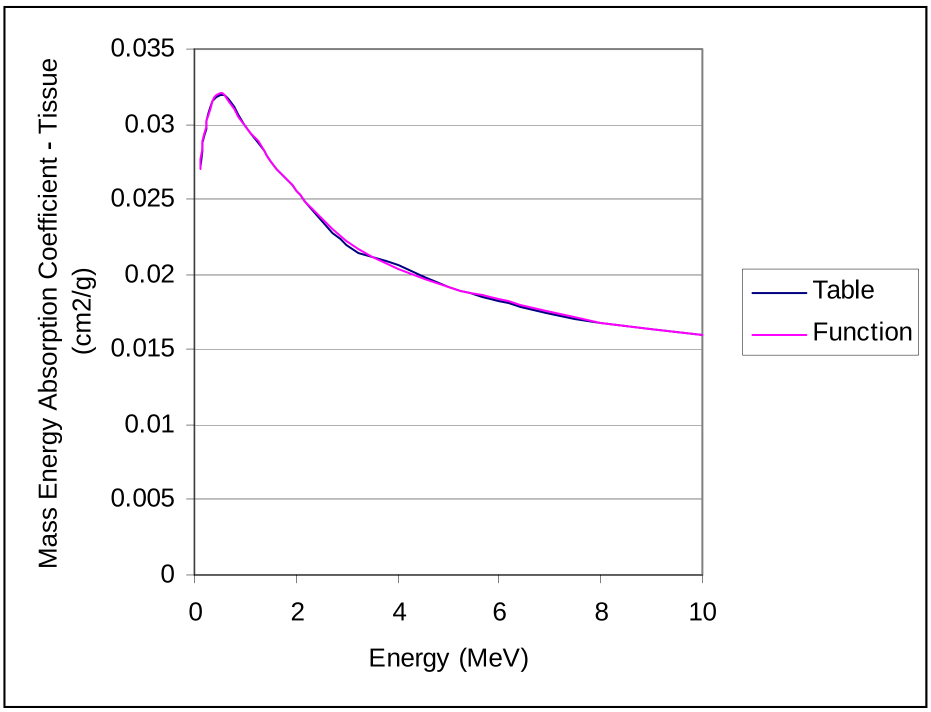


Figure 14: Comparison of Tabular and Functional Fit Values for Mass-Energy Absorption Coefficient for Tissue

8.2.1.5.3 Calculation of the Mass Attenuation Coefficient in Air

The energy-dependent attenuation coefficient for air was fit using a one-term power series given by:

$\mu_{air} = 7.692385x10^{-5}*E^{-0.4530147}$ (8)

The use of this expression results in an error of less than 10 percent between 100 keV and 10 MeV. The fit of the attenuation coefficient for air is shown in Figure 15.

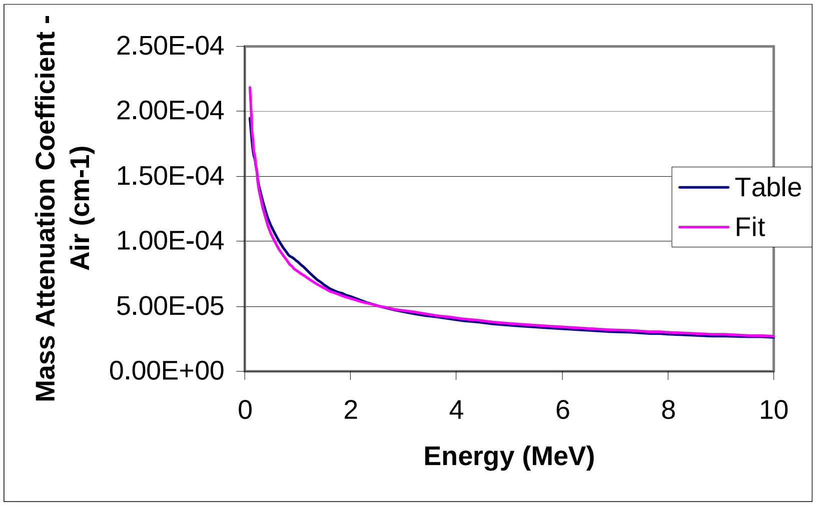


Figure 15: Attenuation Coefficient for Air

8.2.2 <u>Output</u>

The program returns the dose rate at the observer's location based on the source information provided in the configuration file. The total dose received by the observer is also calculated. These values are displayed in the virtual environment as shown in Figure 16.

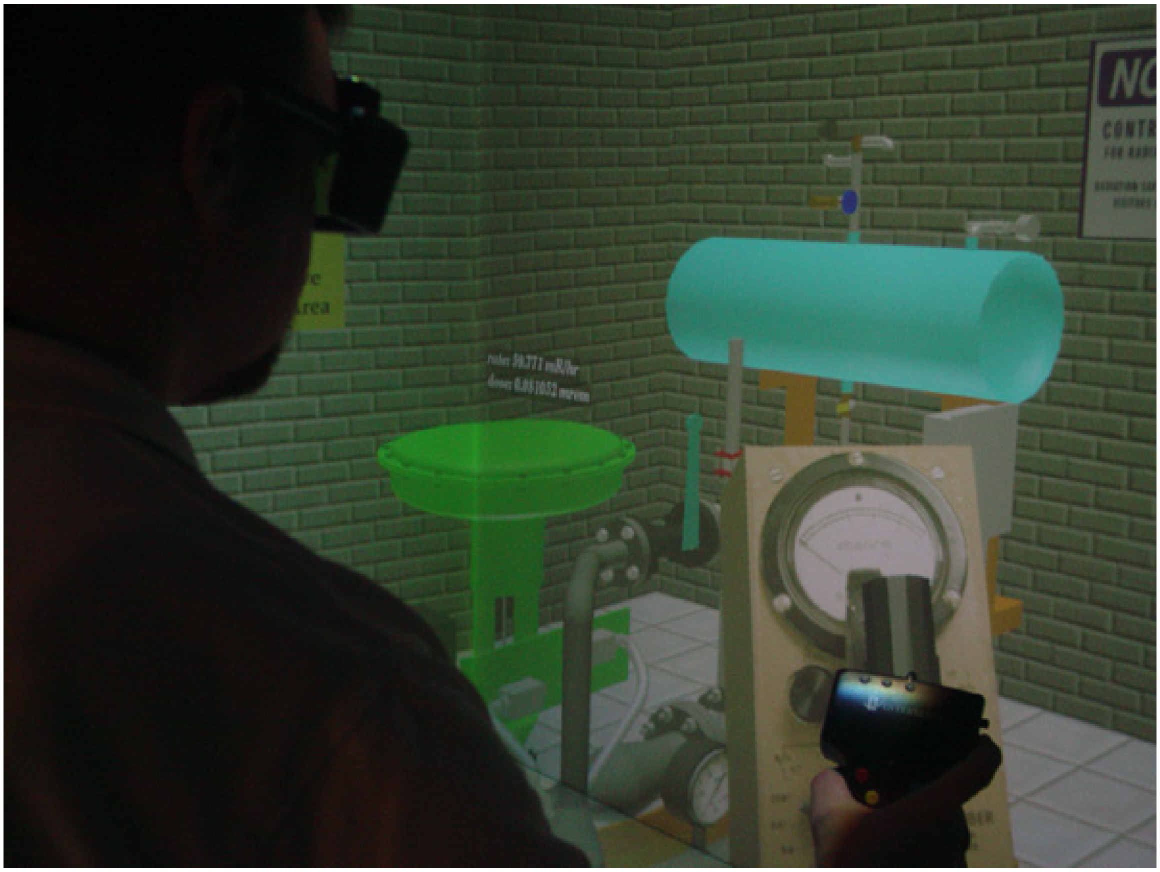


Figure 16: Output from Radiation Dose Model

8.2.3 Validation

In order to verify the performance of the radiation dose model discussed in the previous section, a laboratory experiment was performed with the assistance of personnel from Penn State's Radiation Protection Office. The experiment required the the radiation field generated by a fixed "point" source to be measured using both detectors and electronic dosimeters. The survey meter measured the real-time radiation field, while the dosimeter measured the cumulative dose received at each location. A similar set up was modeled using the VR dose model and the virtual Geiger counter.

The laboratory experiment was performed on a rig that is generally used for calibration of hand-held survey meters. The rig holds 2 Cesium-137 sources (70 milli-Curie and 46 Curie) protected by a shield. A track extends 3 meters from the source shield. The track holds a small cart attached to a digital measuring tape. Detectors can be attached to the cart, and their dose versus distance characteristics can be evaluated. The setup is shown in Figure 17.

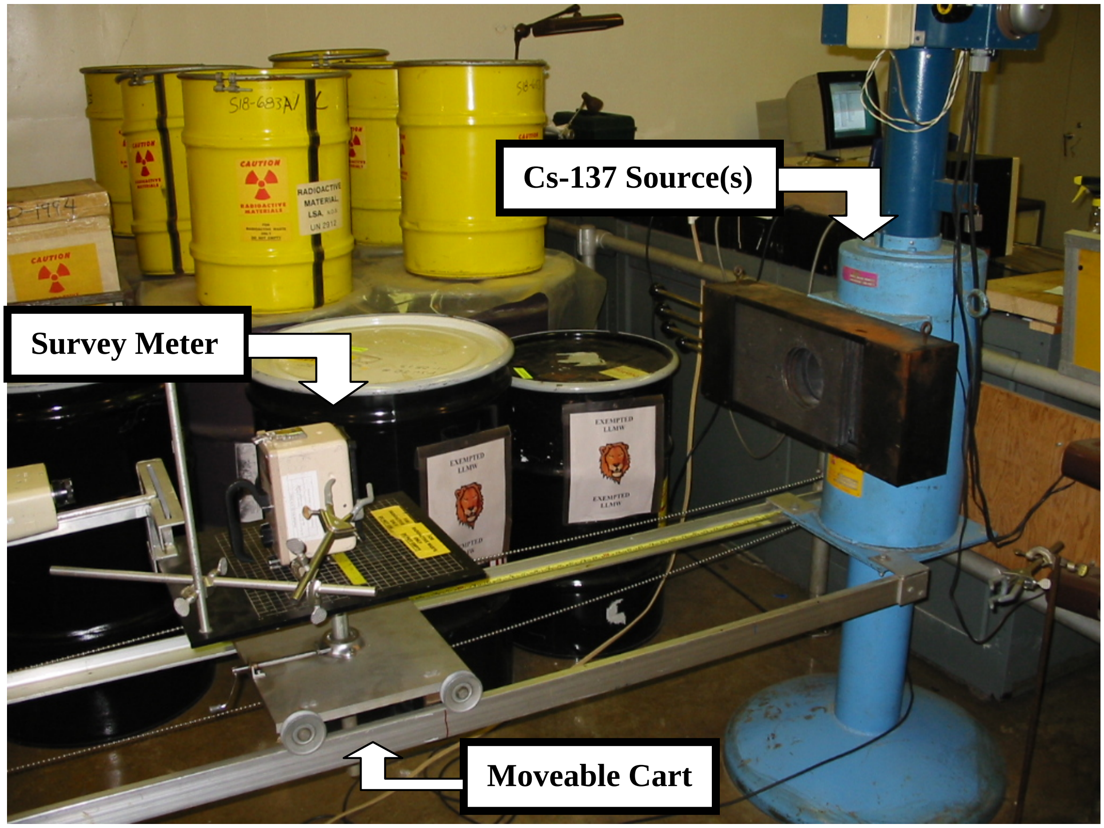


Figure 17: Experimental Set-up for Validation Experiment

Two sets of experiments were performed. Two detectors, an electronic dosimeter and a survey meter, were mounted on the moveable cart. Starting at contact with the source shield, the dose rate and total dose received were recorded for each location at 0.5 meter increments. The detectors were exposed for two minutes at each location.

Two electronic dosimeters were used to measure the cumulative dose. With the weaker source, a "pocket dosimeter" was used because it could be reset after each measurement. With the stronger source, a pager-style SAIC PD-3i was used. Total dose received during the two minute exposure was calculated by subtracting the previous measurement from the new measurement because the dosimeter could not be reset. Although the equipment used for the experiment was not ideal, the results they provided were consistent with hand calculations.

Figure 18 and Figure 19 display the measured and calculated dose rate and the error between the two measurements, respectively, for a small (70 milliCurie) Cesium-137 source. The dose model overestimates the dose rate by a large amount when the detector is close to the source, and the error decreases as the distance increases. The overestimation of the dose rate makes the model conservative, although determining the source of the error and reducing the error require further study. Possible sources of error are the geometry of the source, error in the procedure, detector efficiency, and error in the measurement of the source strength.

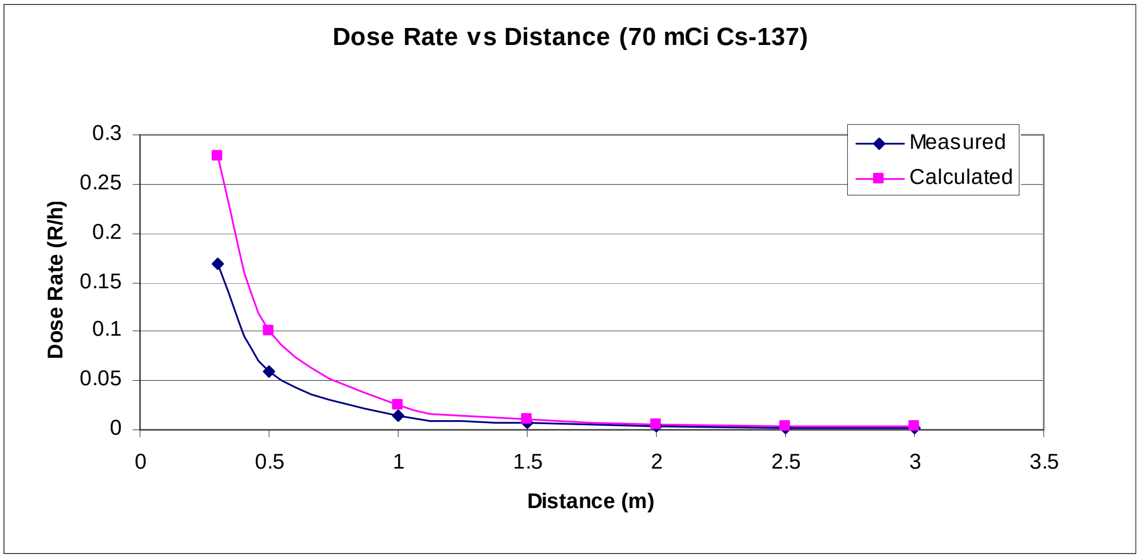


Figure 18: Measured and Calculated Data for Radiation Dose Model with Small Cs-137 Source

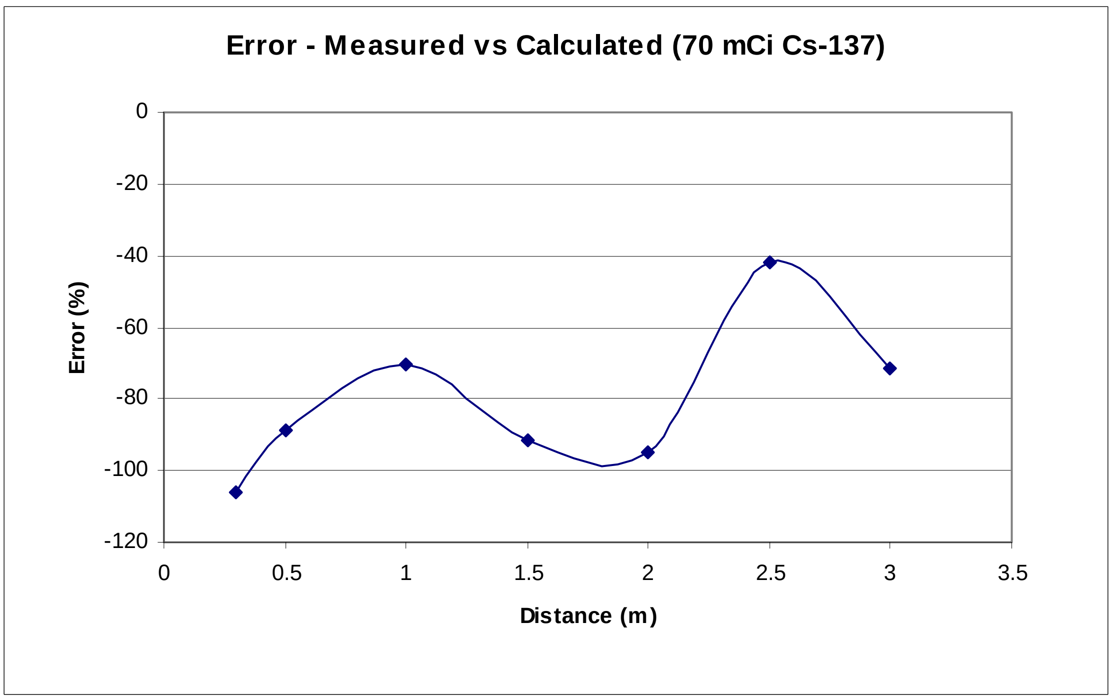


Figure 19: Error in Measurement for Small Cs-137 Source

Figure 20 and Figure 21 display the measured and calculated dose rate and the error between the measurements of dose rate and cumulative dose, respectively, for a large (46 Curie) Cesium-137 source. Again, the dose model overestimates the radiation dose and the cumulative dose. The error appears to be a smaller percentage using the larger source, possibly due to the higher count rate. The dose model functions similar to an ideal detector so errors in detector efficiency and source geometry may account for the error in the measurement; however, additional study is needed.

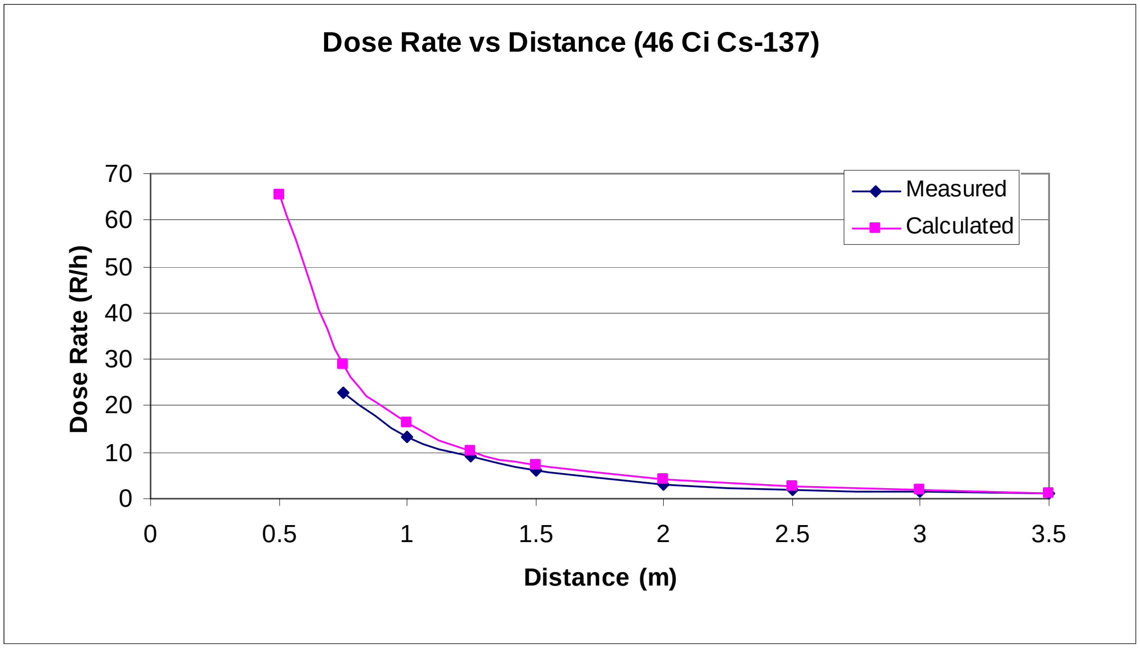


Figure 20: Measured and Calculated Dose Rate for Large Cs-137 Source

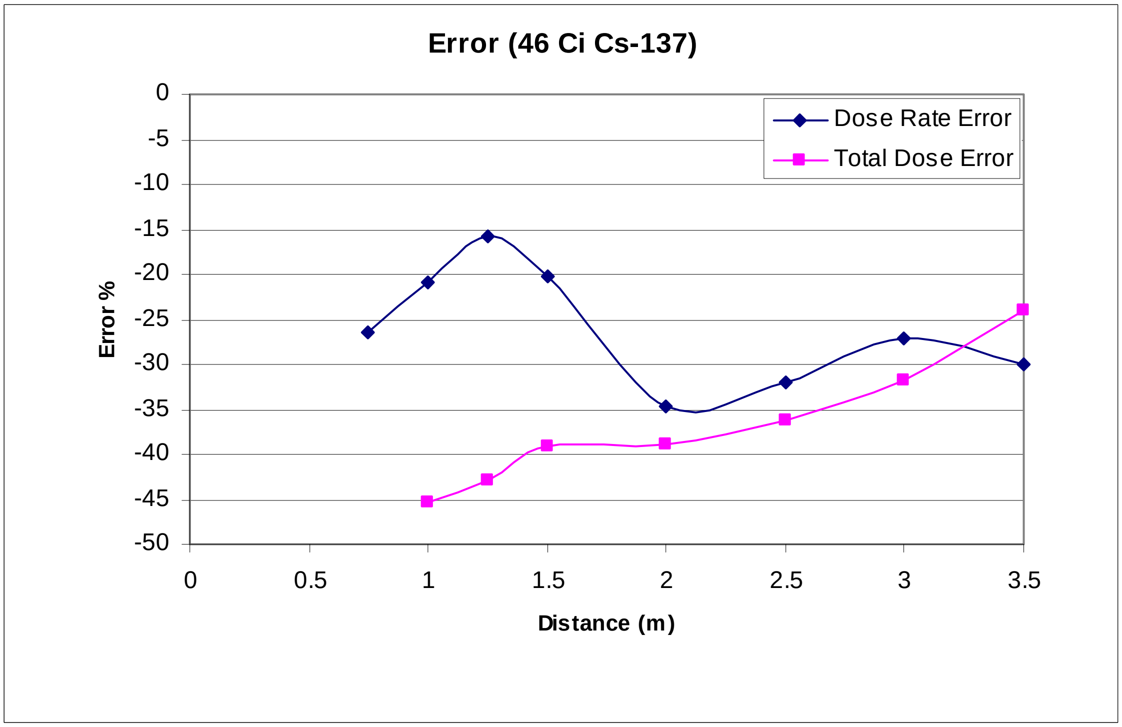


Figure 21: Error in Measurement for Large Cs-137 Source

The radiation dose model was tested using only a Cesium-137 source. Additional sources with multiple gamma-ray energies such as Cobalt-60 should be tested. In its present form, the dose model provides information on the radiation field and the total dose accumulated. The model does not, presently, account for shielding.

Based on field observations, the current radiation dose simulation tools available to training personnel are quite limited. The Teletrix system observed at the Limerick Generating station provides the trainee with some feedback, but it is arbitrary and the meter's reading is left up to the instructor. The Teletrix system is better than no system for mimicking the survey meter readings, since some utilities rely on signs and coaching to inform personnel in training of the radiation field, but this method provides no realistic feedback.

The radiation dose model developed for this work provides realistic feedback for unshielded sources. In order to increase the realism and positively reinforce the ALARA principles of Time, Distance, and Shielding, the dose model should be improved by adding a shielding model. This would greatly increase the complexity of the model since current calculations are performed in real-time. An improved dose model would probably make use of the existing radiation dose modeling scheme for transient sources and some kind of pre-calculated radiation dose field, perhaps an MCNP or Microshield calculation. This technology would require further development.

9 Virtual Mockups Created

Four virtual mockups were created for this task. The first mockup of the AP1000 steam generator compartment was developed for the experiment to be performed for Task 4. The other three mockups are virtual mockups of existing physical mockups at two different power plants' training facilities.

9.1 AP 1000 Steam Generator Compartment

The mockup of the AP 1000 Steam Generator compartment was created from the group of models transmitted to Penn State in April of 2002. Nearly 90 CAD models were determined to be within the concrete "doghouse" that surrounds the steam generator. These models were loaded and viewed to determine their placement within the compartment. Models lying outside of the concrete enclosure were trimmed. This reduced the amount of data shown to be only that which was of interest. Once the data was trimmed, the mockup was assembled and viewed in the CAVE, shown in Figure 22. In order to improve the navigability of the space, transparent geometry was generated and placed over the grating to enable the user to walk on it. Since the grating is created from linear geometry rather than polygonal geometry, the gravity function does not work and this insertion of transparent geometry is necessary.

Figure 22: AP1000 Steam Generator Virtual Mockup

After the walkdown of the model, it was determined that the ADS-4 valves were not loaded and that the work platform was not at the correct elevation. Westinghouse provided updated models, which fixed both issues. Once the issues had been fixed, the mockup was ready for use in the experiment, described in the following section.

9.2 Limerick Pipe Loop

The Limerick pipe loop is a small flow loop used for advanced radiation worker training at the Limerick Generating Station. The loop is comprised of piping of various diameters from 6-inches to 1-inch in addition to a motor-operated valve, a gate valve, a flange, a water supply tank, a small pump, and numerous sample lines. To create the mockup, Robert Miezeiewski of Burns and Roe measured the diameter and length of each pipe segment, noted the valve types and diameters, and traced the electrical and pneumatic lines. In less than a week, he modeled the mockup using the Intergraph PDS modeling package using the as-built measurements. The models were translated into a format that the CAVE can recognize. In order to increase the realism of the mockup, it was placed in a 14’x14’x10’ room with simple textures placed on the walls, floor, and ceiling. An additional texture was placed on the face of the gauge, as shown in Figure 23.

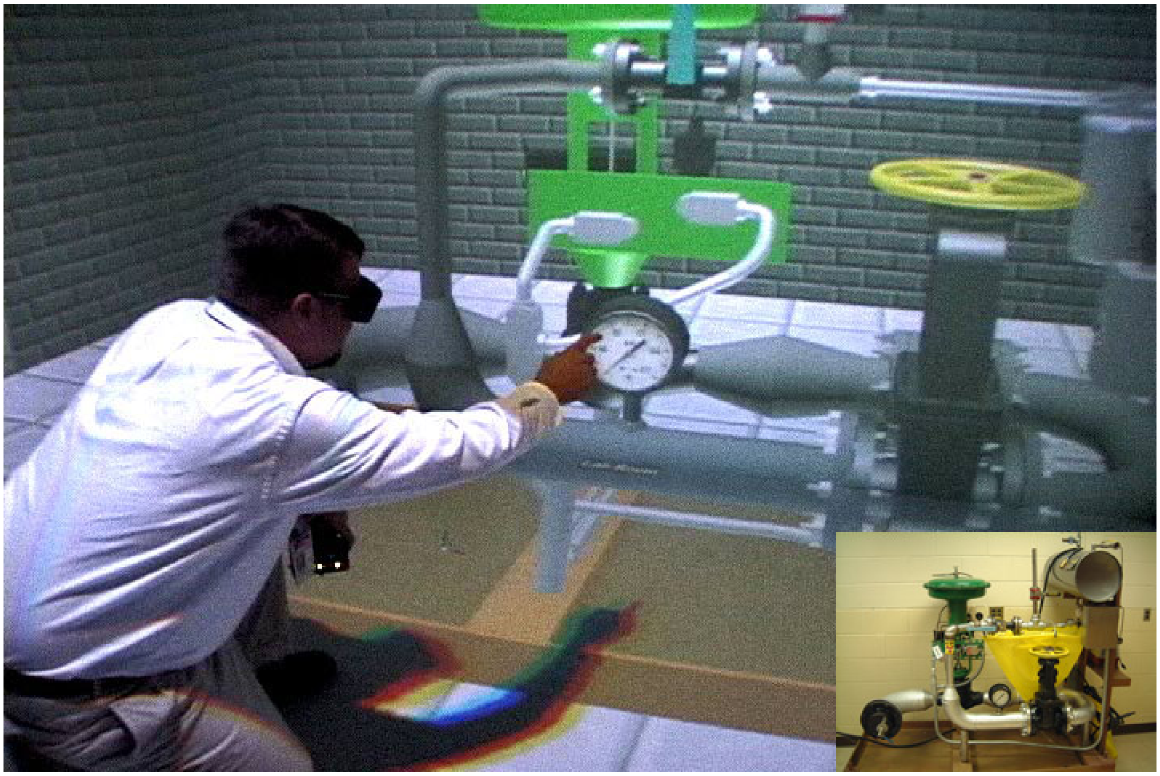


Figure 23: Limerick Pipe Loop Virtual Mockup and Physical Mockup (inset)

This model was developed for possible future experiments comparing tasks in virtual and physical mockups, as well as testing possible methods for generating content in the future.

9.3 SSES Performance Simulator Station

The SSES Performance Simulator Station is one of twelve stations that make-up the performance simulator at the Susquehanna Steam Electric Station. The selected station is typically used for operator training activities, testing and coaching proper work practices such as ALARA and STAR, and testing proper equipment identification techniques. The system can be filled with water so all gauges are functional, and the supply and return pipes and the drain function, as well. In order to create a virtual mockup of this stand, Robert Miezeiewski of Burns and Roe again took measurements of all of the pipes, noted the valve types, and measured the general layout. He created the CAD models of the rig with Intergraph PDS. These models were imported to the CAVE to create a virtual mockup, as depicted in Figure 24. Again, the mockup was placed in the 14x14x10 textured room to provide some context for the user. Textures were placed on the faces of the pressure gauges to add to the realism. This mockup was prepared for possible future experiments comparing tasks in virtual and physical mockups.

Figure 24: Virtual Mockup of SSES Performance Simulator Station

9.4 SSES CCW Mockup

The fourth mockup created is the SSES Closed Cooling Water (CCW) mockup. This mockup is generally used to instruct trades people in the proper assembly and disassembly of equipment. Valves are disassembled and re-assembled, pumps and motors are maintained, and electrical systems are monitored. This mockup is larger than the mockups in the Performance Simulator, and it is designed to be used for more "practical" training. This mockup was modeled in Intergraph PDS by Robert Miezeiewski of Burns and Roe in about 3 weeks. It is more complex than the other 2 physical mockups, which resulted in additional time spent modeling it. Due to the complexity of the model and schedule constraints, some electrical equipment and small-bore tubing was not modeled. The mockup was translated, placed inside a 20'x20'x15' virtual room, and viewed in the CAVE. This mockup is shown in Figure 25.

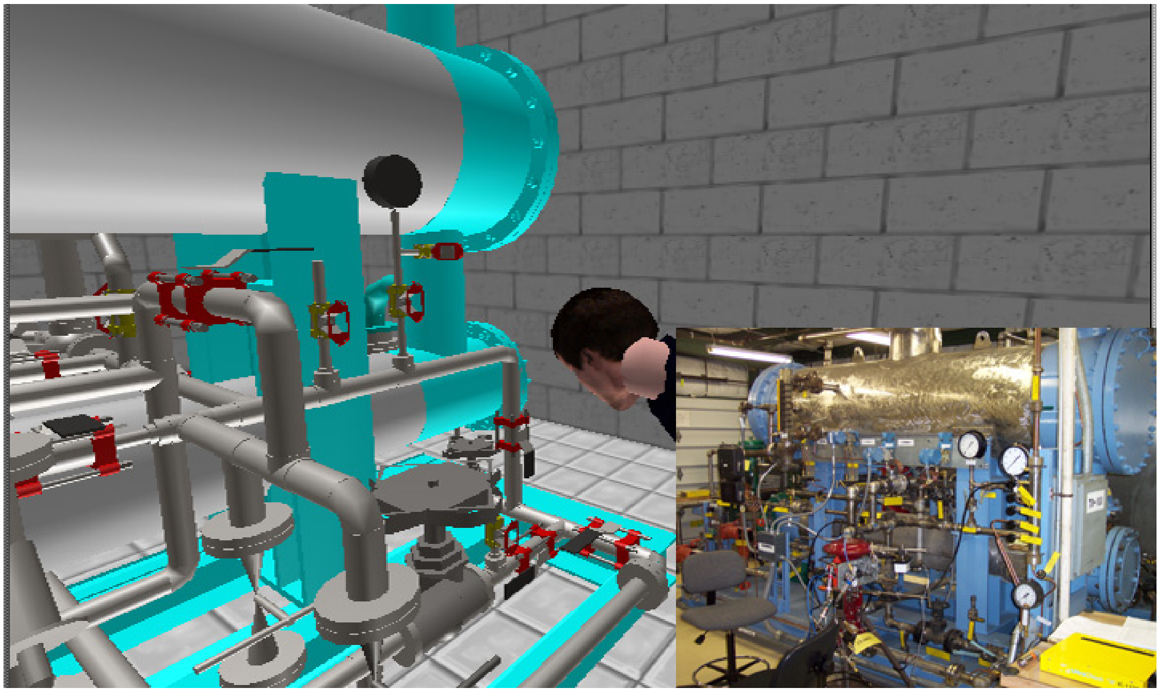


Figure 25: SSES CCW Virtual Mockup and Physical Mockup (inset)

10 Experiments

A number of options were considered for the Task 4 maintenance experiment. The project team considered solving a maintenance tool design problem, evaluating space availability, and examining a proposed maintenance task in the AP1000 model. More specifically, the following tasks were considered:

- Filter replacement in Room 12306
- Design of a pump cart for the reactor coolant pumps
- Vessel head inspection (robot design and UT inspection simulation)
- Steam generator maintenance (sludge lancing, tube plugging, or eddy current testing).

The filter replacement task was considered only briefly since the air handlers in that area are for the non-radioactive ventilation system, and there would be no need for specialized training or the use of the radiation dose model. The design of the pump cart was selected as a possible back-up task since Westinghouse was interested in the removal of the main reactor coolant pump motor for maintenance. The vessel head inspection tasks, while timely, were removed from consideration because they would require a lot of working in an overhead environment, which is difficult without a top-projected ceiling in the CAVE. By process of elimination, a steam generator maintenance task was selected. Since tube plugging and eddy current testing require some work in the overhead, they were not selected. This resulted in steam generator sludge lancing being selected as the maintenance task to be modeled.

One experiment was performed and additional experiments were planned for V. Whisker's thesis work during the effort on Task 4.

10.1 Experiments Performed

Based on the reasoning presented above, steam generator sludge lancing was selected to be the basis for Task 4. Sludge lancing is a common maintenance activity performed during outages at Pressurized Water Reactors. During operation, it is common for a layer of crud to build up on the tubesheet (Figure 26) in the steam generator. If the crud is allowed to work its way down into small gaps between the steam generator tubes and the tube sheet, chemical attack of the tubes can occur. If the chemical attack is allowed to proceed for a sufficient period of time, the walls of the steam generator tube can rupture, in effect causing an interfacial loss of coolant accident (LOCA).

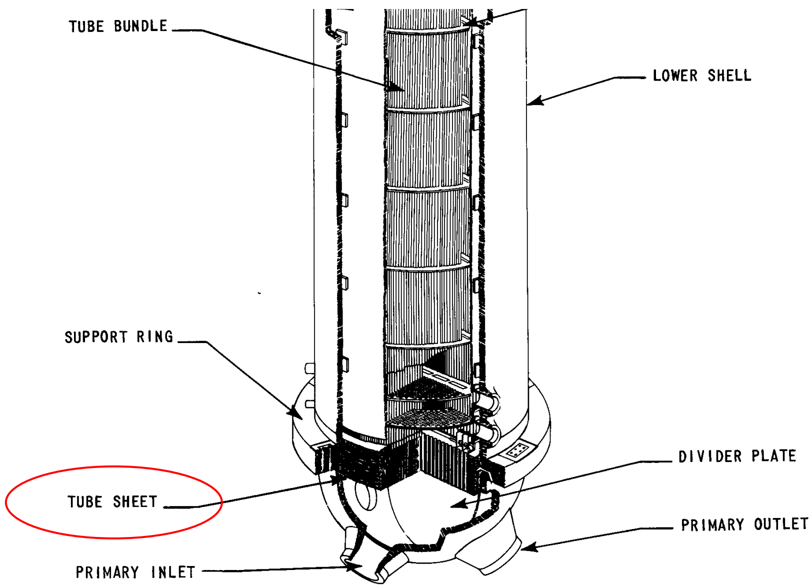


Figure 26: Lower Half of a Westinghouse Steam Generator

To prevent this chemical attack from taking place, a process called sludge lancing is employed. The process is analogous to pressure-washing a deck. High pressure water jets break loose and suspend the sludge in a water flow, which is flushed from the steam generator out into a filter bank where the sludge is removed. The water is returned to the steam generator. Water from small pumps mixed with high pressure are drive the high-pressure water jets. A swirling flow is created by flushing the steam generator with a large volume of water called peripheral flow. The spray nozzles, called sludge lances, are passed back and forth inside area between the u-tubes called the tube lane, to loosen the crud. The level of cleaning required determines the number of passes that the sludge lance must make.

In order to decrease the price of power produced by their advanced plant, Westinghouse decided to uprate the design from 600 MWe to 1000MWe. A number of changes were made to the design to accommodate the higher power output including increasing the height of the containment, using longer fuel rods, and the use of larger steam generators. The use of larger steam generators presents an interesting problem when the sludge lancing task is considered. Table 2 presents the dimensions of the steam drum and the cylinder for the AP 600 and AP 1000 steam generators.

Table 2: Dimensions for AP 600 and AP 1000 Steam Generators

	AP 600	AP1000
Steam Drum	4.45 m (14.6 ft)	5.56 m (18.25 ft)
Cylinder	3.44 m (11.29 ft)	4.39 m (14.4 ft)

The larger steam generators necessary for the power uprate are to be installed in the same compartment as the smaller generators were, meaning that the three foot increase in diameter of the cylinder section leaves three fewer feet of workspace around the generator. The engineers working on the AP 1000 wanted to ensure that sufficient work space was available for maintenance tasks such as sludge lancing.

In order to determine if sufficient workspace was available for this task, a virtual mockup was created. The virtual mockup of the steam generator compartment of the AP1000 was created, as discussed in Section 9.1. Virtual models of the tool crates and equipment used in sludge lancing were created in Multigen-Paradigm's Creator software. These models, such as the M-15 pump in Figure 27, were loaded into the virtual mockup.

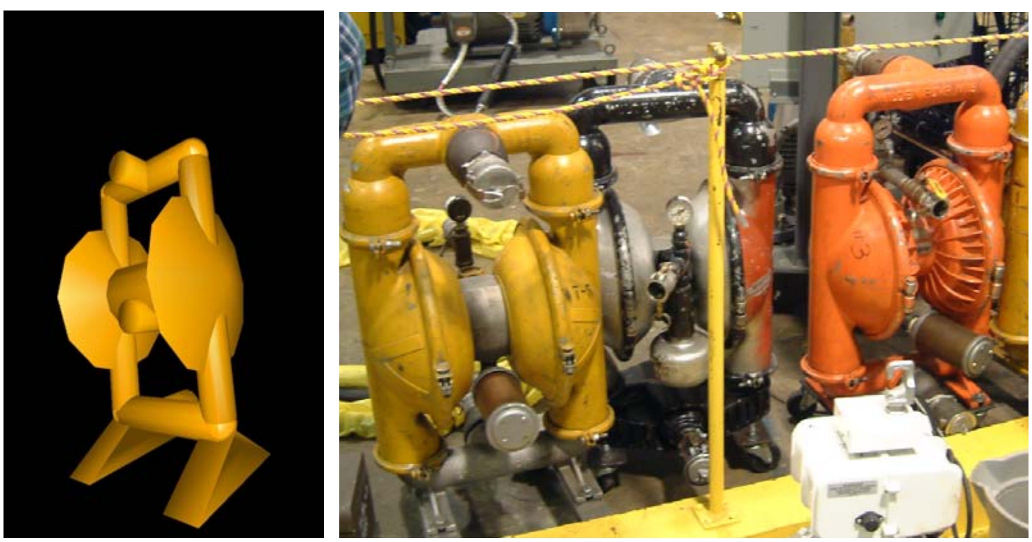


Figure 27: Virtual and Real M-15 Pumps

With input from the Westinghouse Steam Generator Services Personnel at Waltz Mill, the engineers designing the compartment were asked to assess the staging space around the steam generator. The engineers were able to successfully determine that the equipment could be staged.

The next question asked by the designer was whether or not new sludge lancing tools would be required for the new steam generator design. To make this determination, the engineer compared the measurement between the edge of the hand hole, where the sludge lance is inserted to the steam generator, and the concrete wall. In the virtual mockup, this measurement was determined to be about 36 inches. Currently, two sizes of sludge lances are used by Westinghouse. One size is about 30-36 inches and the other is between 12 and 18 inches long. If the shorter sludge lance were used, no redesign will be necessary to accommodate the larger steam generator used by the AP 1000.

10.2 Future Experiments

Based on the training programs observed during the course of this task and taking into account the current capabilities and limitations of the virtual mockup, two additional experiments have been planned for the future. These experiments, involving trained nuclear engineering students, have been planned as a part of V. Whisker's PhD research regarding use of virtual mockups for nuclear power plant training applications. Results will be reported in the PhD dissertation in May of 2006.

10.2.1 Experiment 1

The first area of interest noted in the discussions with the training staffs is personnel dose reduction/radiation awareness. In order to test the virtual mockup's capability in meeting this training need, the following experiment is proposed.

Radiation sources will be placed throughout one of the virtual mockups to instruct the subject on how the dose model functions. The subject will use the virtual survey meter to survey the area and locate the radiation sources. Subjects will be instructed in the proper method of filling out a dose map similar to those recorded by radiation technicians at nuclear power plants. The subjects will then be asked to use the virtual survey meter to fill out a dose map for the area surrounding the virtual mockup.

Once the subjects have become familiar with the functionality of the dose model, they will be immersed in a new virtual environment. In the new virtual environment, they will be asked to locate the radiation sources, determine their strength, and fill out a dose map for the area.

In order to gauge the effectiveness of the training they received in the first virtual mockup, their results will be compared with a control group that did not have the benefit of the training in the virtual mockup. The control group will receive an overview of the functionality of the radiation dose model, but will not receive hands-on training.

The performance of the two groups will be compared. The number of radiation sources located, the time to complete the tasks, the error in dose measurements, and the total dose received while performing the task will be recorded. Subjects will be surveyed to determine their impression of the technology, the ease or difficulty of use, and their understanding of radiation dose reduction.

10.2.2 Experiment 2

The second area of interest is equipment familiarization. In order to evaluate the virtual mockup's effectiveness in familiarizing personnel with the location of equipment and the layout of systems, a second experiment is proposed.

Currently, personnel are introduced to systems and their layouts and locations by a number of methods. These methods include the use of piping and instrumentation diagrams (P&ID), video disc tours, and walkdowns. Each of these methods has drawbacks, however. The video disc tours are expensive to create and offer a limited field of view, basically showing only what the camera captured. Walkdowns probably provide the best familiarization, but there are areas of the plant that are inaccessible during operation. Finally, P&ID diagrams provide only a logical layout of the system rather than a physical layout.

Because of these shortcomings, any new method that can be used for familiarization should be studied. The proposed experiment would proceed as follows:

Two groups of students would be introduced to a hypothetical area of a nuclear power plant, most likely Room 12306 of the AP 600. One group of students would be introduced to the area using P&ID diagrams and pictures, similar to the introduction that one may receive at an operating power plant. The second group of students would be introduced to the space by freely exploring a virtual mockup presented in the CAVE.

The spatial familiarity of the two groups of students will be evaluated by placing them in the virtual mockup and asking them to identify valves and pieces of equipment. Measures of effectiveness will include time to complete the task and number of pieces of equipment identified correctly. Subjects will be surveyed to determine their impression of the technology and the ease or difficulty of use.

11 Conclusions

Full-scale virtual reality mockups, generated in a CAVE environment, are being evaluated for application in power plant maintenance training applications, procedure checkout, and developing maintenance requirements for future nuclear power plants. These mockups are created from 3D CAD models, exported from CAD software in Virtual Reality Modeling Language (VRML) format, and imported to a CAVE immersive display system, where they can be viewed in full-scale and in stereoscopic 3D. The CAVE provides a single user or a small group of users with ease of navigation, ease of interaction, and a true representation of a 3D environment.

The layout of the virtual environment, a room with sufficient space for multiple, concurrent users, encourages collaboration and discussion between users. This can lead to better, more efficient training because additional input can be sought from team members since many activities in nuclear power plant maintenance are team-based. Having additional users in the space provides the ability to draw on their combined experience, resulting in higher confidence levels.

Four virtual mockups were created during this task. Three mockups that model physical mockups used in nuclear power plant training were modeled during the course of this task. These virtual mockups will be used for additional mockup training experiments that will be reported in V.Whisker's PhD dissertation. The fourth mockup, the AP 1000 steam generator compartment, was used to determine whether or not additional tools would need to be developed in order to perform sludge lancing, a common PWR maintenance procedure. In addition, the staging requirements for sludge lancing were evaluated by the engineers from Westinghouse who are designing the space.

The results of the experiment show that the virtual mockup technology can potentially be used to answer some difficult questions early in the design phase of a nuclear power plant. The power uprate from 600 to 1000 Megawatts requires the use of significantly larger steam generators. In order to maintain the layout of the plant, the larger steam generators were inserted into a compartment of the same size as the smaller steam generators. Because of the workspace reduction, the space required for staging the equipment needed for sludge lancing needed to be evaluated. The designer was also interested in determining whether or not new tools would have to be developed to perform sludge lancing on the AP 1000 steam generators.

The engineers used the virtual mockup with input from the maintenance personnel at Waltz Mill, Westinghouse's Steam Generator Services division. The engineers evaluated the equipment staging by moving virtual models of the storage crates and equipment. The engineers felt that there was adequate space to stage the equipment for the sludge lancing activity. To answer the second question regarding the development of the new sludge lancing tool, the engineers measured the space between the steam generator's handhole and the wall. It was determined to be the same as many of the operating plants so there was no need to develop new tools since the existing tools were adequate.

Two additional experiments have been planned during this phase of research. These experiments will be performed in the future, and the results will be reported in V. Whisker's PhD dissertation. These experiments focus on the use of virtual mockups for common nuclear power plant training applications such as radiation awareness training and equipment familiarization training.

The experiments performed during this task only scratch the surface of potential applications for virtual reality mockups for nuclear power plant training. Additional research is required to actually quantify the benefits of using these mockups to supplement current training activities. In addition to training for the current generation of nuclear power plants, virtual reality could benefit future nuclear power plants. Additional work is needed to evaluate the development of training simulators for the next generation of nuclear power plants.

12 Opportunities for Further Research

Additional effort is required in order to create virtual mockups that respond to input from the user. It is possible to create geometry that can be manipulated by the user, but the process is cumbersome. Working with the geometry created by commercial CAD packages makes the virtual mockups easy to create, but the translation process used to import the mockups to the CAVE results in poorly organized hierarchical trees. These trees must be manipulated in order to create mockups that respond to interaction. The process of animating and interacting with the virtual mockups requires further development.

The ability to model and simulate radiation environments, the accurate portrayal of 3D environments, and the ability to train individuals or teams in the same space are unique to the CAVE. Further experiments, such as those proposed in this report, are required to quantify the benefits, if any, of using virtual mockups for nuclear power plant training applications.

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Appendix

13.1 Software Descriptions

A number of software packages were used to develop the virtual mockup.

13.1.1 Bentley MicroStation

MicroStation is a design tool, which allows users to develop 3-D CAD models of objects. The models and all of their components are graphical simulations of real-world objects. From design and engineering through construction and operation, the model holds all information about the asset and its configuration, simplifying project management and making the operation of the facility more efficient and cost-effective.

The models used in the virtual mockup were created using Intergraph's PDS software; however, the project team has been using MicroStation to perform all model conversion from the 3-D CAD to Open Inventor format for use in the CAVE. MicroStation allows the user to export models as VRML 1.0 files for viewing.

13.1.2 Unigraphics NX

Unigraphics NX is another design tool used to create 3-D CAD models. This package is currently being used to create and refine the design of the Pebble Bed Modular Reactor. Unigraphics NX can export models in native format (*.jt, *.prt), parasolids format (*.x_t), and VRML (*.wrl) format.

13.1.3 Open Inventor

Open Inventor™ is an object-oriented toolkit used to develop 3-D graphics applications. In addition, it defines a standard file format for exchanging 3-D data between applications. Open Inventor serves as the basis for the VRML (Virtual Reality Modeling Language) standard. Since Open Inventor and VRML are related, model conversion from VRML 1.0 to Open Inventor is a simple process, which is performed by a Perl script. The Perl script used to convert models from VRML to Open Inventor appears in the appendix of this report. Additional information about Open Inventor may be found at http://www.sgi.com/software/inventor/.

13.1.4 Performer

OpenGL Performer provides a programming interface for developers to create simulations and 3-D graphics applications. According to Silicon Graphics, Performer applications may be used to simplify development of complex applications used for visual simulation, simulation-based design, virtual reality, interactive entertainment, broadcast video, architectural walk-through, and computer aided design. For the virtual mockup project, Performer is used to interpret and display the graphical objects created using three-dimensional CAD. Information about Performer may be found at http://www.sgi.com/software/performer/overview.html.

13.1.5 Vega

Vega is a modular real-time simulation environment. Developed by MultiGen-Paradigm, Vega allows the user to develop real-time visual and audio simulations. The software contains interfaces for sensors, virtual reality tools, and other visualization applications.

Vega provides a graphical user interface, Lynx, which allows viewpoints, controls, and lighting to be easily added to the virtual environment. More information about the Vega software can be located at www.multigen.com/products/runtime/vega/index.shtml.

13.1.6 Explorer

Explorer is an interactive data analysis tool for desktop and immersive environments including large format Immersive Projection Displays (IPDs) such as CAVEs™ developed at Penn State ARL. It accepts several standard 3-D graphics formats including VRML, DXF, OBJ, OpenInventor, OpenFlight, 3DS, and Performer. In addition to supporting the graphics, Explorer supports quad-channel sonification of sounds within the 3-D environment, providing a truly immersive 3-D experience.

Explorer operates in concert with standard six degree-of-freedom motion tracking systems, such as the Intersense IS-900, to track the position and orientation of the user and several input devices within the immersive environment. This allows the user to use gestures, which facilitates a human centered approach to navigation and interaction with the virtual world. Navigation through the 3-D space is simply a matter of pointing to the desired direction of travel.

Explorer provides a base set of user/model interactions that can be extended through the Multigen Vega Software application programming interface (API). These interactions include:

- Animation Control (for animated models: pause, resume, faster, slower)
- Grab / Move / Release / Undo
- Queries (distance to point, position of point, object identification)
- Virtual Tools including tape measure, crane, wrench, screwdriver, blowtorch, Geiger counter
- Gravity Modeling
- Collision Detection
- Position Bookmarking

Explorer utilizes the DIS/HLA protocol to link simultaneous Explorer applications running on separate machines. This can potentially allow users in another room or across the country to collaborate in the virtual mockup.

13.2 Results of laboratory experiment testing radiation dose model

Source	Cs-137	Energy	661 keV			Strength	Large	46.4	Ci	Small	0.07097	Ci	GAMMA	0.33	R/hr/Ci at 1m
Distance	Time (s)	Dose Rate R/h (measured)	Dose Rate (calculated)	Dose Rate (Expected)2	Error (M-E)	Error (M-C)	Dose mrem (measured)	Dose mrem corrected (Dx1.32)	Dose mrem (expected)	Dose mrem (calculated)	Error	Source	Attenuator 1,2,4,10,100	Dosimeter	Source (Bq)
0	120					#DIV/0!			0.000		#DIV/0!	Small	1		2.63E+09
0.3	120	0.169	0.279	0.2602233	-0.4602235	-65.0888	3.42	4.5144	5.633	9.300	-106.007	Small	1	Pocket	2.63E+09
0.5	180	0.06	0.1002	0.0936804	-1.8666667	-67	2.01	2.6532	3.000	5.010	-88.8286	Small	1	Pocket	2.63E+09
1	120	0.015	0.02495	0.0234201	-1.8666667	-66.3333	0.37	0.4884	0.500	0.832	-70.2839	Small	1	Pocket	2.63E+09
1.5	120	0.007	0.01138	0.0104089	2.984127	-62.5714	0.15	0.198	0.233	0.379	-91.5825	Small	1	Pocket	2.63E+09
2	120	0.00365	0.00618	0.005855	-4.6575342	-69.3151	0.08	0.1056	0.122	0.206	-95.0758	Small	1	Pocket	2.63E+09
2.5	120	0.0025	0.003937	0.0037472	2.208	-57.48	0.07	0.0924	0.083	0.131	-42.0274	Small	1	Pocket	2.63E+09
3	120	0.0017	0.00272	0.0026022	0.130719	-60	0.04	0.0528	0.057	0.091	-71.7172	Small	1	Pocket	2.63E+09

Source	Cs-137	Energy	661 keV			Strength	Large	46.4	Ci	Small	0.07097	Ci	GAMMA	0.33	R/hr/Ci at 1m
Distance	Time (s)	Dose Rate R/h (measured)	Dose Rate (R/h) (calculated)	Dose Rate (Expected)2	Error (M-E)	Error (M-C)	Dose mrem (measured)	Dose mrem corrected (Dx1.0)	Dose mrem (expected)	Dose mrem (calculated)	Error	Source	Attenuator 1,2,4,10,100	Dosimeter	Source (Bq)
0	120					#DIV/0!			0.000		#DIV/0!	Large	1		1.7168E+12
0.5	120		65.54	61.248		#DIV/0!		0	0.000	2184.667	#DIV/0!	Large	1		1.7168E+12
0.75	120	23	29.068	27.221333	4.6956522	-26.3826		0	766.667	968.933	#DIV/0!	Large	1		1.7168E+12
1	120	13.5	16.31	15.312	8.6666667	-20.8148	374	374	450.000	543.667	-45.3654	Large	1	PD-3i (#5262)	1.7168E+12
1.25	120	9	10.416	9.79968	12.32	-15.7333	243	243	300.000	347.200	-42.8807	Large	1	PD-3i (#5262)	1.7168E+12
1.5	120	6	7.216	6.8053333	8.6666667	-20.2667	173	173	200.000	240.533	-39.0366	Large	1	PD-3i (#5262)	1.7168E+12
2	120	3	4.04	3.828	-2.75	-34.6667	97	97	100.000	134.667	-38.8316	Large	1	PD-3i (#5262)	1.7168E+12
2.5	120	1.95	2.574	2.44992	-1.1692308	-32	63	63	65.000	85.800	-36.1905	Large	1	PD-3i (#5262)	1.7168E+12
3	120	1.4	1.779	1.7013333	2.1428571	-27.0714	45	45	46.667	59.300	-31.7778	Large	1	PD-3i (#5262)	1.7168E+12
3.5	120	1	1.301	1.2499592	-0.6530612	-30.1	35	35	33.333	43.367	-23.9048	Large	1	PD-3i (#5262)	1.7168E+12