Final Report

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Executive Summary:

The objective of this multi-phase 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. This report presents the results of the completed project.

Much of the development of the virtual mockup has taken place at Penn State ARL's SEA Lab facility. The SEA Lab facility includes a fully-immersive 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. Together these tools provide the user with a believable virtual reality experience.

The virtual mockup was tested as a design review tool by performing an independent mock design review on Room 12306 in the AP 600. The reviewers identified a number of design changes that were required. The virtual mockup is an excellent tool for design review for a number of reasons. The mockup provides the user with simple navigation using a point-and-go motion model. Geometry is rendered in full-scale, stereoscopic 3-D, which gives users a better sense of scale and depth perception than they can get from a desktop computer system.

Experienced construction superintendents used the tool to develop, review, and optimize the modular construction sequence in a room in the AP 600. The superintendents were able to reduce their initial installation time by nearly 30 percent using the virtual mockup. This demonstrates the potential of the virtual mockup as a tool for nuclear power plant construction planning.

Two maintenance activities were evaluated using the virtual mockup. The designer of the AP 1000 was able to answer two questions regarding the maintainability of the AP 1000 steam generator using the virtual mockup. The equipment staging requirements and workspace availability for sludge lancing were confirmed in the virtual mockup.

The first two activities performed under this project are ready to play a role today in the design and construction planning of the next generation of nuclear power plants. The results of this project demonstrate that full-scale virtual mockups can be used as an effective tool for design review of commercial nuclear power plants. The technology is capable to play a limited role in construction/constructability analyses of next-generation nuclear power plants. Additional development and testing are required before the virtual mockup technology can be used for nuclear power operation and maintenance applications, however.

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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 Immersive Projection Display (IPD) 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 to improve arrangements and reduce both construction and maintenance costs, as has been done by building full-scale physical mockups.

2 Project Overview

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, this testbed will be used to study the effectiveness of the technology to support the development and evaluation of the installation sequence for the selected space. The third task involves developing the methodology and the required tools to perform a prototypical maintenance task using the virtual mockup. The actual maintenance activity study will be performed as task four. Finally, an investigation into the lessons learned during the first four tasks as they apply to a Generation IV design will be performed.

2.1 Task 1 Description

The first task entails the creation of a virtual mock-up of a selected space in the AP600/1000 nuclear power plant. The specific actions performed to create the virtual mockup involve identification and acquisition of 3D CAD drawings of the selected space, conversion from 3D CAD format to a format recognized by the Immersive Projection Display (IPD) system, and integration of a virtual environment application to support the functionality required supporting the installation study objectives. Once a mockup has been developed, it will be evaluated for completeness, including ensuring that all of the pieces of the room have been received. The mockup application will be tested for effectiveness at supporting the installation and maintenance study objectives. The level of detail shown by the mockup will be evaluated to determine whether or not the level of detail is sufficient to proceed with Tasks 2, 3, and 4. The optimum breakdown of the 3D CAD models will be determined. The options include the module level, the system level, and the individual component level. Finally, the project team will be surveyed to determine potential uses of the virtual mockup and technologies required for implementation to provide direction for future research specifically relevant to the nuclear industry, as well as to evaluate whether the objectives and goals of Task 1 were achieved.

2.2 Task 2 Description

The second task entails testing the virtual mockup developed during Task 1 for its suitability in modeling modular power plant construction. The mockup will be evaluated by performing a module installation sequence review and by interactively developing installation sequences to determine potential savings in schedule time and rework. During this task, the mockup will also be evaluated for its usefulness in design reviews. Westinghouse personnel will review the installation sequence development tools during a simulated module installation.

2.3 Task 3 Description

During Task 3, the tools necessary to perform Task 4 will be developed. These will include development of a higher-fidelity mockup of a yet-to-be-chosen area in the plant for use in the simulated maintenance activity in Task 4. Westinghouse will assist Penn State in training student “workers” to perform the maintenance activity.

2.4 Task 4 Description

A simulated maintenance activity will be performed during Task 4. This activity will be supervised by personnel from Westinghouse, Burns and Roe, and Panlyon. The project team and an independent reviewer will assess the workers’ performances as well as the suitability of the virtual mockup as a training tool.

2.5 Task 5 Description

Task 5 entails applying the lessons learned from the previous four tasks to a Generation IV nuclear power plant design, most likely the Pebble Bed Modular Reactor (PBMR) or the Gas Turbine-Modular High Temperature Reactor (GT-MHR). The feasibility of performing similar installation sequencing studies and maintenance activities using the virtual mockup will be determined.

3 Background

This section provides some background on virtual reality technology and the creation of full-scale virtual reality mockups.

3.1 Classes of Virtual Reality

Two categories of virtual reality technology are often discussed. These are desktop virtual reality and immersive virtual reality.

Desktop virtual reality is a first-person, 3-D simulation presented on a desktop monitor. These simulations can range from a first-person walkthrough to a first person shooter video game. Interactions can range from environments where users may only view

objects to an environment where the user can move objects. A depiction of desktop virtual reality is shown in Figure 1.

Figure 1: Desktop Virtual Reality

Immersive virtual reality encompasses Head Mounted Displays (HMD) and Immersive Projection Displays (IPD). Immersive virtual reality provides the user with a more complete view of a virtual environment, often with a large field of view that appears to surround the user. Head mounted displays have small screens mounted in front of the eyes in a helmet-like device worn on the head. HMDs provide a lower cost solution for presenting the immersive form of virtual reality, but they can be uncomfortable to wear for long durations and may contribute to simulator sickness. IPDs generally rear-project computer generated images on large screens. A number of different formats exist, but the most well-known is probably the CAVE Automatic Virtual Environment (CAVE). IPDs provide the highest fidelity projection of a virtual environment, but they can be very expensive. These technologies are shown in Figure 2.

Figure 2: Immersive Virtual Reality Technology: IPD (l) and HMD (r)

3.2 Penn State ARL's CAVE

Penn State ARL's Synthetic Environment Applications Lab (SEA Lab) houses a five-sided virtual reality display system, 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 3.

Figure 3: 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 4.

Figure 4: 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 5.

Figure 5: MiniTrax Wand

Used together, the tools provide a means of interacting with the high-fidelity simulation.

3.3 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 6: 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.

3.4 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 7.

Figure 7: Creating Full-scale Virtual Mockups from CAD Models

Creating virtual mockups from CAD models has advantages and disadvantages. Reactor designers are generally working with some sort of 3D CAD based product model as they design future nuclear power plants. This makes CAD models for future designs easy to obtain. The models created by the designers are typically of high visual fidelity, modeling systems in great detail so the virtual mockup's use of the CAD recreates the design quite accurately. This accuracy, however, can be a disadvantage. The high level of detail inherent in the CAD models can lead to a high polygon count, which results in a slow rendering frame rate. The slow frame rate decreases a user's sense of being immersed in the virtual mockup. Fortunately, there are strategies available for managing the frame rate and reducing the polygon count of the models. A number of

commercially-available software tools such as Okino's Polytrans or Systems in Motion's Rational Reducer may be used to reduce the number of polygons used to render the CAD models.

Creating the virtual reality mockups from CAD models has one additional disadvantage. Because the models cannot be rendered in the CAVE directly in their native format, file conversion tools must be used, as was discussed above. These file conversion tools export models of varying quality. Most tools deliver a final model that is visually accurate, but all hierarchical information embedded in the model is generally lost. This complicates the use of the model later in training and maintenance applications, although it does not make it impossible. In addition, the file translations, at this point, discard any additional "meta-data" that is embedded in the CAD model such as the type of metal used, the equipment vendor, etc.

While the process of creating full-scale virtual mockups using CAD models currently has some disadvantages, the benefits to the designer outweigh these drawbacks. As the technology advances, it may be possible to render the models with their meta-data and hierarchical structure intact. During the course of this research program, a number of work-arounds for these issues have been noted. In addition, the disadvantages generally apply to the future programs related to operation and maintenance familiarization and training in the virtual environment, rather than design or construction review that are nearer term items.

4 Virtual Mockups Created

Six virtual mockups were created. Room 12306 of the AP 600 nuclear power plant served as a testbed for most of the tasks of this research program. A full-scale mockup of the AP 1000 containment was created as well as a mockup of the AP1000 steam generator compartment. The three additional mockups are virtual mockups of existing physical mockups at two different power plants' training facilities. A proof-of-concept mockup of the reactor cavity of the PBMR was also created, which is discussed in the final section of this report.

4.1 AP 600 Auxiliary Building Room 12306

The testbed used for the first two tasks is a full-scale, virtual reality mockup of Room 12306 in the Westinghouse AP600 nuclear power plant. Room 12306 lies between the containment building and the turbine building. This room is located on the third level of the Auxiliary Building, in the northeast corner. The inside dimensions of this room are approximately 46'-0" x 16'-0" x 15'-6".

A single controlled access is provided to this room from the Turbine Building, through the north wall. Room 12306 contains normally non-radioactive, mechanical equipment and piping. The room also serves as a containment piping penetration area; therefore, it contains containment isolation valves for several fluid systems.

The selected space contains components, piping, valves, and instrumentation associated with ten different fluid systems. This room also contains a number of pre-assembled equipment modules. The most significant module located in this room is the Passive Containment Cooling System (PCS) Pump and Valve Module, a large, two-level, structurally framed module. This module contains major components of the Passive Containment Cooling System and containment isolation valves associated with other fluid systems.

The following ten fluid systems are represented in Room 12306.

1. Compressed and Instrument Air System
2. Chemical and Volume Control System
3. Demineralized Water Transfer and Storage System
4. Fire Protection System
5. Passive Containment Cooling System
6. Steam Generator System
7. Central Chilled Water System
8. Non-Radioactive Water System
9. Hot Water Heating System
10. Liquid Radwaste System

4.1.1 Tour of the NPP Virtual Mockup

The virtual mockup of Room 12306 developed under Task 1 is comprised of approximately 50 CAD model files. The larger pieces, assembled from the CAD files, are described in this section. To show the relative location of each image, Figure 8 has been assembled using a side view of the desktop 3-D CAD of Room 12306. Images taken in the CAVE showing the largest module, KB-36, the off-module platform, the fire protection system valve station, and the air-handling units are presented.

Figure 8: Location of Major Equipment in Room 12306

Figure 9 shows a user on the first level of Room 12306. Module KB-36, a large, 2-level module, occupies much of the south end of the mockup. Piping, valves, and equipment for the passive containment cooling system dominate the first level of the module. In the figure, a number of valves can be seen as well as a heater and a chemical addition tank.

Figure 9: Module KB-36 - First Floor

Figure 10 shows the second floor of module KB-36. Piping and valves from a number of different systems are present; mainly the chemical and volume control system, liquid radwaste system, and demineralized water system.

Figure 10: Module KB-36 - Second Floor

Figure 11 shows the off-module platform, which supports four air-operated valves. Two parallel pipes, the steam generator blowdown lines, run from the containment shield wall at the south end to the turbine building at the north end.

Figure 11: Steam Generator Blowdown Lines and Off-Module Platform

The fire protection system containment isolation valve station, shown in Figure 12, occupies the first level of the North end of Room 12306. The valve station will be installed as a prefabricated assembly. In addition, the doorway between this room in the auxiliary building and the turbine building is shown.

Figure 12: Fire Protection System Containment Isolation Valve Station

Figure 13 shows the air handling units and associated equipment on the second level of the virtual mockup. Hot water and chilled water lines enter the air handling units. Ductwork connects to the air handling units and exits through the wall at the north end.

Figure 13: Air Handling Units on the Second Level

4.2 AP 1000 Containment

A virtual mockup of the containment of the AP 1000 was created from a group of models transmitted to Penn State from Westinghouse in April of 2002. Over 450 files were converted to create the virtual mockup. A spatialization tool was developed to allow very large models to be displayed with an acceptable frame rate. Geometry of a size less than a certain cutoff value is not displayed, which increases the frame rate of the display remarkably, making the model navigable. While this tool is not necessary for simpler spaces, such as Room 12306, it is very beneficial for larger spaces.

The AP 1000 containment was a large mockup, created from more than 800,000 triangles. The mockup displays all of the major equipment within the AP 1000's containment shell – the reactor vessel, two steam generators, two core makeup tanks, two accumulators, and the in-containment refueling water storage tank (IRWST). The virtual mock is a good familiarization tool for the evolutionary design. It has been used for undergraduate education and for promoting the AP 1000 nuclear power plant design.

Figure 14: Virtual Mockup of AP 1000 Containment

4.3 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 15. 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 15: AP1000 Steam Generator Virtual Mockup

4.4 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 Mizeiewski 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 16.

Figure 16: 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.

4.5 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 Mizeiewski 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 17. 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 17: Virtual Mockup of SSES Performance Simulator Station

4.6 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 18.

Figure 18: SSES CCW Virtual Mockup and Physical Mockup (inset)

5 Virtual Mockup Capabilities

The software driving the virtual mockup enables the user to perform many tasks. The wand, shown in Figure 5, controls many of these tasks. The wand enables the user to navigate through the virtual environment. The virtual environment uses a “point-and-go” motion model, which means the user need only point the wand in the desired direction of travel and push forward on the multi-directional joystick to move in that direction. The user can move in any direction, including flying to locations that would not normally be accessible.

The wand has 5 programmable buttons. For example, the green button enables the user to toggle gravity (ground clamping) on and off, and the yellow button enables the user to step forward through an installation sequence. The red button controls a virtual toolbox. Some of the virtual tools are listed in Table 1 below.

Table 1: Virtual Mockup Tools

Tool	Function
Hand	User can grab and move objects
Measuring Tape	A virtual measuring tape – measures the distance between 2 points
Screwdriver	A virtual screwdriver
Wrench	A virtual wrench
Torch	A virtual blowtorch
Ruler	A 12-inch ruler
Geiger Counter	A virtual survey meter – works with the radiation dose model
Marker	Enables user to place markers at points of interest - saves those positions in a file

The measuring tape and the grab function are triggered by bringing up the appropriate tool and pulling the trigger button. The measuring tape function measures the distance between two points, as shown in Figure 19. The grab function enables the user to move geometry. The user points at the geometry with the wand, pulls the trigger, and moves the wand, which causes the object to move, also.

Figure 19: Using the Virtual Measuring Tape

6 Virtual Mockup Survey

In order to have a quantifiable metric for measuring the effectiveness of the virtual mockup, a survey was developed. Adapted from work by Tatum, *et al*, at Newport News Shipbuilding, the survey compares physical mockups, the desktop CAD application, and the virtual mockup in a number of different categories. (Tatum, 1994) Responses were solicited from participants during a meeting of the project team. Eight responses were received, representing a number of different fields and positions within companies including an Engineering Project Manager, a Vice-President of Engineering, an Operations Instruction Shift Manger from a utility, a Health Physics Instructor from a utility, an engineering consultant, and a Director of CAE.

Two statistical tests were used to reduce the data. First, a two-sided t-test with unequal variances was used to determine if a relationship existed between the three pairs of

methods: Computer and Virtual model (CV), Computer and Physical model (CP), and Virtual and Physical model (VP). This test was performed on each question to determine trends as well as on each survey response to determine if their answers were related. The second test, performed using the ANOVA method, reduced the data for each question to determine if a relationship exists among all three methods: desktop CAD, virtual mockup, and physical mockup.

Table 2 gives the mean and standard deviation corresponding to the eight survey responses for each question. After the area of interest, the next three columns give the means for the computer model, the virtual mockup, and the physical mockup, respectively. Following the means, the standard deviation for each data set has been calculated. The means appear to show that the respondents felt strongly about the utility provided by the computer model and the virtual mockup. The physical mockup scored poorly in most areas due to its high cost and difficulty to change. The large fluctuations in the standard deviation on some questions indicate disagreement among the respondents concerning the usefulness of a technology for that particular aspect.

Table 2: Mean and Standard Deviation Data for Each Survey Question

	Average Computer	Average Virtual	Average Physical	SD Computer	SD Virtual	SD Physical
Preliminary design concept evaluations	8.00	6.25	2.00	2.12	2.95	1.41
Location of equipment and systems	8.25	8.13	5.00	1.85	2.62	2.87
Space Perception	5.00	9.63	6.00	2.00	0.99	2.78
System Review	7.63	7.50	3.75	2.00	1.58	1.39
Interference Analysis	6.63	6.63	5.13	1.68	0.99	2.67
Access	4.38	7.88	4.00	2.73	1.76	3.02
Operability	3.50	7.38	5.38	2.13	1.92	2.75
Maintenance	3.88	7.00	5.13	1.40	1.85	3.14
Design Fitup	7.88	7.63	3.50	1.31	1.58	1.60
Configuration management	7.00	6.63	3.25	1.85	1.58	3.24
Identification of material usage	6.50	4.38	1.63	1.97	3.51	0.99
Verification of design requirements	7.38	5.50	2.50	1.92	2.55	1.88
System engineering calculations and analyses	5.13	3.88	1.75	1.47	3.08	2.21
Design to ensure construction requirements are considered	5.00	6.50	4.00	0.75	2.56	3.20
Illumination evaluation	3.50	6.00	3.00	1.37	2.47	3.02
Demonstration of equipment removal	5.00	9.00	4.50	2.31	1.80	2.35
Drawing development	6.50	3.88	2.75	1.97	2.06	3.48
Support transfer of digital data for construction	7.63	5.88	1.50	1.48	3.55	0.87
Analyze proposed design modification	6.63	8.00	4.50	1.68	2.12	1.66
Advanced reactor design development support	7.25	7.25	4.25	1.48	1.79	2.44
Evaluation of previous designs	7.00	7.50	4.88	1.85	1.58	2.76
Portability	7.63	3.25	3.00	1.48	2.11	2.00
Verification of Class 1 piping requirement	7.25	5.88	3.50	1.48	2.62	1.66

The results of the statistical tests performed on the data for each question are shown in Table 3. The second, third, and fourth columns show the probability generated using Student's T-Test on pairs of technologies. The second column compares the computer model and the physical mockup; the third column compares the virtual mockup and the physical model, and the fourth column compares the computer model and the virtual mockup. A high probability determined using the T-Ratio indicates that the means of the data set are closely related. This can be perceived as an indication that the respondents felt that the pair of technologies performed equally for that specific task. Probabilities generated using the T-test that are greater than 0.5 are highlighted in orange, while probabilities between 0.1 and 0.5 are highlighted in green. This indicates that the respondents felt that the technologies could possibly be used for the same purpose. The final column in the table represents the results of an analysis of the variance (ANOVA) performed on the combination of all three technologies. Higher values of the ANOVA indicate that there is no perceived relationship between the data sets. Conversely, lower values of the ANOVA indicate that there is a relationship between the data sets. An ANOVA result of one would indicate that all three data sets perform equally well or poorly for the task in question.

Table 3: T-Test and ANOVA Results for Each Survey Question

	Probability C-P	Probability V-P	Probability C-V	ANOVA
Preliminary design concept evaluations	0.00	0.01	0.23	13.16
Location of equipment and systems	0.03	0.05	0.92	3.839
Space Perception	0.45	0.01	0.00	9.766
System Review	0.00	0.00	0.90	12.09
Interference Analysis	0.10	0.29	0.26	2.725
Access	0.74	0.02	0.06	3.66
Operability	0.34	0.12	0.01	3.78
Maintenance	0.34	0.18	0.00	3.82
Design Fitup	0.00	0.00	0.11	17.89
Configuration management	0.02	0.08	0.18	5.449
Identification of material usage	0.00	0.07	0.05	10.96
Verification of design requirements	0.00	0.02	0.13	10.37
System engineering calculations and analyses	0.00	0.13	0.09	6.784
Design to ensure construction requirements are considered	0.17	0.11	0.51	2.142
Illumination evaluation	0.39	0.05	0.09	3.035
Demonstration of equipment removal	0.37	0.00	0.02	8.026
Drawing development	0.01	0.45	0.01	6.524
Support transfer of digital data for construction	0.00	0.01	0.08	16.32
Analyze proposed design modification	0.01	0.00	0.69	7.399
Advanced reactor design development support	0.00	0.02	0.27	7.612
Evaluation of previous designs	0.03	0.05	0.61	4.153
Portability	0.00	0.82	0.00	18.37
Verification of Class 1 piping requirement	0.00	0.07	0.06	9.275

In order to evaluate each respondent's overall feelings, the mean, standard deviation, and T-Test probability were calculated. These data are shown in Table 4. Overall, most respondents felt that the computer model was the best overall for the tasks evaluated, with the virtual mockup coming in second. Most respondents rated the physical mockup poorly; however, this may be due, in part, to a discussion concerning scale models and physical mockups and their high cost during the meeting.

Table 4: Mean, Standard Deviation, and T-Ratios for each Survey

	Survey 1			Survey 2			Survey 3			Survey 4			Survey 5			Survey 6			Survey 7			Survey 8		
Mean:	8.43	6.74	2.83	8.00	5.26	5.30	6.13	8.60	2.83	7.87	7.30	2.48	7.20	7.57	4.39	6.14	7.18	3.27	6.13	5.43	6.22	8.39	7.91	3.70
Std Dev:	1.88	2.33	2.62	2.13	3.38	3.43	1.89	1.50	1.28	2.52	2.35	1.35	1.60	2.53	1.99	2.72	3.01	2.20	1.51	2.04	3.22	1.76	1.79	2.01
	CP	CV	VP	CP	CV	VP	CP	CV	VP	CP	CV	VP	CP	CV	VP	CP	CV	VP	CP	CV	VP	CP	CV	VP
T-Test Probability	0.00	0.01	0.00	0.00	0.00	0.97	0.00	0.00	0.00	0.00	0.45	0.00	0.02	0.71	0.00	0.00	0.24	0.00	0.91	0.21	0.34	0.00	0.38	0.00

6.1.1 Summary of Survey Results

A number of conclusions can be drawn from the survey results. Based on the mean calculated for each survey question, areas in which each technology performed well can be listed.

The virtual mockup scored strongly in the following categories:

- Space perception
- Interference analysis
- Access
- Operability
- Maintenance
- Ensuring construction requirements are met
- Illumination evaluation
- Demonstration of equipment removal
- Analysis of proposed design modifications
- Advanced reactor design development support
- Evaluation of previous designs

The virtual mockup was rated highly in areas where good spatial correlation and visualization are critical. As stated before, the sense of presence experienced by the user is one of the virtual mockup's strengths. The survey results make this clear.

The desktop CAD system scored strongly in the following areas:

- Preliminary design concept evaluations
- Location of equipment and systems
- System review
- Interference analysis
- Design fitup

- Configuration management
- Identification of material usage
- Verification of design requirements
- Drawing development
- Support of digital data transfer for construction
- Advanced reactor design development support
- Portability
- Verification of Class 1 piping requirements

The desktop CAD system received the highest scores in areas in which 3D CAD systems are typically used, design-oriented tasks. A number of the strengths of the CAD system are the result of its link to a database, which contains information about material specifications, part numbers, suppliers, and part names. It may be possible to add some of these features to the virtual mockup; however, it is not clear if there would be value-added over the desktop CAD display if this were done.

The physical mockup scored strongly in the following areas:

- Space perception
- Interference analysis
- Maintenance
- Operability

The physical mockup did not receive the highest score in any of the categories, although it scored well in the categories relating to spatial understanding, like those mentioned above.

The survey and associated statistical data reduction provided the project team with results that were consistent with the discussions of the strengths and weaknesses of each technology.

7 Performing Design Reviews in the CAVE

During the course of the project, the designer made a number of modifications to the arrangement of the components in Room 12306. Penn State received updated models based on these modifications from the designer. This provided an opportunity to evaluate the virtual mockup technology for performing pre- and post change reviews.

Design reviews are typically performed using desktop computer applications driving either monitors or large-screen displays. When Penn State received the initial package of models from the designer, a cursory design review was made in the virtual mockup. Prior to consultation with the designer, a number of items of interest were located. The designer was consulted and all were known issues; however, they had not been addressed. The purpose of the design review was not to prompt design changes, rather, it was meant to show that the virtual mockup technology is useful. A number of the known issues are described in the following paragraphs.

Figure 20 depicts the south end of the first floor of module KB-36. The top figure shows the initial version received from the designer. The bottom figure shows the latest version received. The general layout of the space has remained the same; however, small changes to some of the valve locations can be seen.

Figure 20: Before (top) and After (bottom) of the South End of the First Floor

Figure 21 shows the north end of the first floor of Room12306. A number of changes in pipe routings were made between the initial version, shown in the top image, and the final version, shown in the bottom image. The routing of some of the fire protection system and the compressed and instrument air system was changed to eliminate interferences and to improve overhead clearance on the first level.

Figure 21: Before (top) and After (bottom) Views of the North End of the First Floor

One area of interest found in the initial walkthrough is shown in Figure 22. One of the valves on the first level within module KB-36 is in a position that would be very difficult for a worker to operate. Many of the valves on the first level are operated infrequently; however, this valve, part of the passive containment cooling system, was located in a

position behind a valve and below another valve. In addition, the valve is canted away from the user. Because of this, the valve is not only hard to reach, but it may also be operated incorrectly because of its orientation. The valve was moved to a more accessible location in the latest iteration of the mockup, shown in the bottom image.

Figure 22: Before (top) and After (bottom) Views of Difficult-to-Reach Valve

During an early evaluation of the virtual mockup, one of the engineers reviewing the layout of the systems noticed the pipe interference shown in the top image of Figure 23.

A one-inch compressed air pipe was intersecting a four-inch fire protection pipe. This interference was resolved by re-routing the compressed air pipe, shown in the bottom image.

Figure 23: Before (top) and After (bottom) Views of Pipe Interference

Figure 24 shows the relocation of the fire hose station from the west wall to the east wall. On the west wall, the fire hose station was difficult to access because it was placed

behind the fire protection system containment isolation valve station. The top image shows that the CAD data for this system was received while a design change was being processed, because the pipe connecting the fire hose to the fire protection system is already present on the east wall.

Figure 24: Before (top) and After (bottom) Views of Fire Hose Station

Figure 25 shows before and after images of a mismatch between two fire protection system pipes, their penetrations, and the holes through the concrete to the stairwell on the other side of the wall. In order to support the air handling units and associated piping, the

roof slab of this area was thickened. This required moving the fire protection system piping down so that it did not intersect with the new slab. The pipes on the far side of the wall were moved down; however, when the initial set of models was received from the designer, the change had not been made to the near side. In the latest set of models received, the routing of the pipes has been changed so they mate with the penetrations.

Figure 25: Before (top) and After (bottom) Views of Pipe-Penetration Mismatch

The examples highlighted between Figure 20 and Figure 25 show before and after views of some of the design changes to the virtual mockup testbed over the first year of the project. These examples may be used to demonstrate the value of the virtual mockup in

evaluating design issues from an operability and maintainability perspective. The images show how a design evolves over time. The virtual mockup presents a snapshot of individual times in the design process.

Apparent errors in the design are often due to configuration management issues. When designing in a multi-organization environment, design changes may in-process but do not yet appear in the final version of the CAD used by the lead design office. The one-to-one scale view provided by the IPD system may be used to quickly determine if requested changes have been worked in to the final version of the CAD.

Two of the examples presented in this section stand out. First, the tilted valve demonstrates the value of the virtual mockup in suggesting alternative layouts. Second, recognition of the mismatch between the FPS pipes and penetrations shows the mockup's value as a tool for reviewing design integration.

Figure 22 shows a change in the valve position due to its inaccessibility. The human-in-the-loop interaction provided by the virtual mockup demonstrated that it would be difficult to reach the valve in its previous location. By breaking the model down into finer detail in which individual valves could be identified and moved, more accessible potential locations were suggested.

Figure 25 may be used to demonstrate the virtual mockup's usefulness as a design integration tool. Two different engineering firms designed the piping systems on each side of the concrete wall. These firms send the completed models to the vendor for design integration. One design firm had made the appropriate changes when the roof was thickened, while the other had not. An immersive display system would allow the vendor to easily recognize whether or not the appropriate changes were made to the models.

8 Using Virtual Mockups for Modular Construction Planning

Many of the next-generation nuclear power plant designs, including the GE/Hitachi ABWR, the AECL CANDU-6 and ACR-700, and the Westinghouse AP-600 and AP-1000, are slated to be constructed from prefabricated modules.

Modules are typically built off-site in a shipyard or other large-scale manufacturing facility and then transported to the construction site by barge or rail for final assembly. Because of this, the order of installation of the modules and the spool pieces that connect them becomes a concern. The virtual reality system developed during this project provides a method of studying this installation in greater detail than is typically achieved. Installation sequences can be modeled full-scale, in high resolution so that it is possible to view virtual construction. Development of realistic construction schedules and sequences is the key to taking advantage of the benefits offered by modularization.

The nuclear industry has begun to adopt some of these practices for the development and planning of construction for the next generation of nuclear power plants (Gen III and Gen

III+). One of the first applications of 4-D construction simulation was performed by Westinghouse in work supported by the Electric Power Research Institute (EPRI). The project involved simulating the first nine months of construction of an AP600 nuclear power plant using industry standard desktop 4-D CAD tools. The simulation was created by linking the Primavera scheduling software to the CAD models created in Intergraph's PDS software. The project demonstrated the usefulness of developing a 4-D CAD representation of nuclear power plant construction.

Currently, the development and viewing of 4-D models using commercially-available schedule simulation software is performed on desktop computers. This task aims to extend this concept of the 4-D model by allowing a user to develop construction sequences and to view the space being constructed in full one-to-one scale.

8.1 Schedule Simulation Software

Commercially available schedule simulation software packages, such as Bentley Schedule Simulator or Intergraph Schedule Review, allow users to link CAD models to schedule activities creating 4-D models. The 4-D models of the construction schedule can be animated once the linking between the schedule and the geometry is complete. In typical desktop 4-D software, objects can be programmed to appear transparent or in false-color prior to being installed. During the installation activity, the objects appear in another color. Finally, once installation has been completed, the objects appear in full color. The use of color allows the user to track the progress throughout the construction sequence.

The functionality offered by the desktop visualization software has been reproduced within the CAVE using software developed at Penn State. Taking advantage of some of the functionality in VRML, three versions of each object have been created for use during the three stages of construction. First, a gray version of each model may be used as a placeholder, showing the position of equipment or reserved space prior to installation. Second, a red version of the model is loaded to show the object as it is being installed. Finally, the full-color version is loaded once the piece has been installed. Based on feedback from users of the system, schedules are typically visualized in the CAVE without using the gray versions of the geometry. This allows the user to observe the installation of each piece, as it would appear during the actual construction of the space.

A configuration file (*.cfg), loaded at the same time as the geometry, contains the lines of text that control the animation of the installation sequence. Each line of the installation sequence section contains the start time and end time for each activity, as well as the name of the object being installed at that time. Currently, all information must be input manually by the user. The software accommodates the scheduling and visualizing of concurrent activities. If desired, the user may input module names rather than individual object names, which simplifies the verbal announcement of the parts currently being installed.

8.1.1 Playback

The schedule may be visualized in the virtual reality system after the configuration file has been loaded. Delivering the ANIMATE command triggers the playback of the animated construction sequence, allowing users to watch as the room is constructed around them. As the pieces are installed, text-to-speech software announces the object name or module name of the piece currently being installed to assist the user with orientation. The user may pause the simulation at any time by speaking the STOP command. The animation will resume once the START command has been issued. Once the playback of the installation sequence has been completed, the user can restart the sequence using the RESTART command. When the simulation is paused or has been completed, the user may advance through the schedule step-by-step using FORWARD and BACKWARD commands. These commands allow the user to examine areas more closely for details that may have been missed during the animation, as well as to look for constructability issues, such as difficult-to-reach weld locations or module boundaries that could be moved.

8.1.1.1 Interactive Sequence Development

In addition to facilitating the review of construction sequences, the software developed at Penn State also allows users to interactively create new sequences. In order to make the interactive creation of schedules easier, a number of virtual environment tools have been developed. First, the user may query the part name or object name using the IDENTIFY function. The IDENTIFY function displays the part name next to the object until the CLEAR LABELS command is spoken. Second, the SELECT function allows the user to select objects by pointing at them and issuing the SELECT command. Selected objects change color from full-color to red. The color change provides a visual means of determining which pieces have not yet been scheduled for installation. If an object is selected out of sequence, the UNSELECT command can be used return the object to an unselected state. Alternating between the IDENTIFY and SELECT commands, the user can interactively develop the installation sequence for all objects within a space. Figure 26 depicts views of piping before and after selection. In order to view the sequence, the user must set up a configuration file for the sequence manually using the object names given by the IDENTIFY command. If further development is warranted, this activity could be automated to speed the schedule development process.

Figure 26: Demonstration of SELECT Function (Before and After)

8.2 Experiments Developed

Two experiments were developed to investigate the application of Immersive Virtual Environments for improving the schedule reliability and confidence of project planners prior to facility construction. The first experiment tested interactive installation sequence development tools to ensure the software and process functioned as planned, and the second experiment tested the inclusion of the virtual environment as a review tool in the current construction sequence development workflow. These experiments are discussed further in the following sections.

8.2.1 Experiment 1

The first experiment was a proof-of-principle test to evaluate the software functionality that facilitates the creation of installation sequences by construction superintendents or similar trades people in the virtual environment. The subjects, construction management graduate students from Penn State, had no prior knowledge of the plant design or the specific area represented by the virtual mockup. The participants were given a brief scripted introduction to the mockup and the modules within Room 12306. Then, they were asked to develop an installation sequence for the modules and the makeup pieces using the interactive tools in the virtual mockup. The sequence was translated into the proper format for the configuration file described in the previous section. The participants were then able to review the installation sequence in the virtual environment and make necessary changes to the sequence based on the review. A diagram of the flow of the experiment is shown in Figure 27.

Figure 27: Flowchart for Experiment 1

The results of the first experiment were primarily qualitative observations aimed at improving the software and the process that were to be used for the second experiment, although the inexperienced participants successfully used the software to develop reasonable construction sequences and found a number of potential constructability issues. These results are discussed further in Section 8.2.3.

8.2.2 Experiment 2

The second experiment investigated the addition of schedule review in the immersive virtual reality technology to the current schedule development workflow in order to improve schedule reliability/confidence of project teams. In addition, the participants interactively developed an installation sequence while immersed in the virtual environment, similar to the procedure developed for the first experiment.

Two teams of two experienced Burns and Roe construction superintendents participated in the experiment. Each team received a complete set of 3-D isometric drawings depicting the modules, assemblies, and makeup pieces from Room 12306. They were tasked with the development of a construction plan for Room 12306, which included a construction schedule and a list of potential conflicts and opportunities for improving the constructability of the space. The teams were allotted two days for the schedule development. Once the schedules were generated, participants completed a survey to evaluate their level of confidence in the construction plan. The construction plan generated by each team was sent to Penn State where it was translated for display in the virtual environment. The teams visited the SEA Lab at Penn State ARL where they reviewed and analyzed their construction plans. After the reviews, each team was interviewed to record the constructability issues identified, conflicts resolved, and schedule reliability/confidence achieved. A comparison of the participant's level of confidence was performed using these interviews and the questionnaires collected prior to and after the analysis in the virtual environment. During the initial viewing of the schedules, the teams were asked to identify design changes or sequence changes they would like to see. These changes were incorporated into a new version of each sequence. Finally, the teams were asked, as a group, to interactively develop a schedule. The flow of the second experiment is depicted in Figure 28. The results of the experiment are discussed in the next section.

Figure 28: Flowchart for Experiment 2

8.2.3 Experimental Results

The results of the two installation sequence development experiments are described in the following sections.

8.2.3.1 Results of Experiment 1

After a tour of the layout of Room 12306, the participants interactively developed an installation sequence for the space. Each team presented a clear strategy for their work plan; however, each of the teams developed a unique sequence. One team began by installing the large modules and makeup pieces at the south (containment) end of the room, gradually making their way to the door to the turbine building at the north end. The second team installed pieces starting from top to bottom and from the ends of the room towards the middle. Upon playback of the installation sequence, they were able to recognize that their sequence was not easily constructible and made appropriate changes. Both teams were able to develop reasonable installation sequences by reviewing their creations in the virtual environment and making changes.

The interactive sequence development lasted less than one hour for each group. The sequences were played back and critiqued by the participants. The playback allowed the subjects to find additional places where parallel activities could be performed, as well as places where the schedule they had developed could be improved.

Being immersed in the virtual mockup of Room 12306 before and during construction fostered discussion of the actual methods of construction that could be used. For example, the subjects discussed the use of spreader beams for lifting long sections of pipe into place, and they mentioned module size limitations for open-top construction and accessibility issues for some of the field weld locations. The presentation of the space in immersive 4-D enhanced the participants' spatial understanding of the space allowing them to consider workspace interference between trades while they planned multiple of parallel activities. Using the immersive schedule development software, the subjects developed reasonable installation sequences with no prior introduction to the space and little experience in nuclear power plant construction.

8.2.3.2 Changes Required Following Experiment 1

As expected, the first experiment exposed some shortfalls in the strategy and execution planned for the second experiment. The subjects noted that the granularity and the resolution of many of the models were sufficient; however, they requested that the makeup pieces be divided at the appropriate field weld locations, as they would be during the actual installation. The appropriate changes to the models were completed prior to the execution of the second experiment. Other than the model granularity issue, the subjects did not mention any difficulty in using the system. The participants suggested additional functionality, such as the announcement of the part name being installed, to provide additional benefits to the users of the system.

Based on experience gained from the first experiment, changes were made to the mockup to accommodate the possibility of additional schedule activities. Prior to the first experiment, a number of refinements were made to the original CAD models received from the designer, in order to facilitate the model's use for installation simulations. Originally, the construction sequence for Room 12306 was comprised of 9 steps. The virtual mockup consisted of 7 assemblies, 5 sets of makeup pieces, and a total of 40 model objects. Since the five sets of makeup pieces were deemed insufficient for developing a realistic installation sequence by the participants in the first experiment, each of the makeup piece models was subdivided, resulting in more than 25 individual makeup pieces. As mentioned previously, the subjects noted that it would be helpful to model the actual pipe pieces, cut at field weld locations. Because of this, the additional refinements were made once the isometric drawings were received from the designer, namely the spool pieces were subdivided to reflect the presence of field welds. After the refinements, up to 51 steps, 6 or 7 assemblies, 45 makeup pieces, and 75 model objects were available to the construction planner.

8.2.4 Experiment 2

The participants in the second experiment, experienced construction superintendents from Burns and Roe Enterprises, were provided with 3-D isometric drawings of the modules and makeup pieces. They were given a maximum of 48-hours to develop a construction plan for the Room 12306 using the paper drawings. Penn State received the construction schedules created by the two groups. These schedules were converted to a format that could be displayed in the virtual environment. One team documented the schedule in Microsoft Excel where activities were broken down by man-hours, while the second team created the schedule using the Primavera project management software, allowing one day for each activity. To create a 4-D construction simulation, each schedule activity was matched to an object model. The time scale used in the configuration file was scaled to match the length of time the teams allotted for each activity so the sequences could be compared.

Each team viewed their sequence in the virtual environment after a brief scripted introduction to virtual reality and the virtual mockup. After the sequence was played back from start to finish, the teams advanced through the sequence step-by-step and

evaluated their performance, while discussing their construction strategy with the researchers. The following section discusses their findings during the review.

8.2.4.1 Areas of Interest

During the review, each group found a number of issues with their construction sequences. The participants pointed out two areas in particular that required further study.

The first area of interest was the off-module platform, which supports four air-operated valves and two four-inch pipes. Using the 3-D CAD drawings provided, it was unclear that four makeup pieces of varying diameters pass underneath the platform, complicating the sequence of installation. Each group discussed possible strategies for installing the makeup pieces and the platform. One group suggested installing the platform without the decking to allow more access to the area underneath, while the other group suggested installing the makeup pieces first and then the platform. The groups were weighing the possibility of damaging the pipes underneath during the lift against ease of installation and inspection.

Another area of interest to the participants was one of the containment isolation valve stations. The valve station was designed to be installed as a prefabricated assembly. One group divided the installation of the assembly into two separate lifts. The first lift placed the assembly in a lay down space above its final location. The second lift would move the assembly into place so that installation could be completed. The two lifts were intended to allow access for workers and equipment to a nearby doorway to be maintained. During their design review, however, another software feature, a measuring tape, was used to determine that sufficient clearance around the assembly was maintained. The second group chose to install the valve station in one lift, although they decided that some of the weld locations would have to be moved to improve access and constructability.

Once the participants had refined their installation sequence to their satisfaction, the changes they requested were incorporated into the configuration file. At that time both teams were invited to view the playback of the two sequences. This activity was performed to simulate a design review where two construction alternatives were presented. The groups discussed each other's development strategy and the associated tradeoffs of the methods used.

8.2.5 Issues Identified

The participants identified a number of areas that could be changed to improve the constructability of Room 12306 during their review:

- Support locations and field weld locations could be changed to make welding easier and to provide adequate space for radiography of welds in a number of places, most notably those surrounding the off-module platform and the fire protection system containment isolation valve station. It should be noted that the

support locations shown in the current 3-D model are not necessarily the final support/hanger locations.

- Participants identified areas where multiple crews could work in parallel to improve the efficiency of the installation. Using the virtual environment, participants were able to determine that sufficient space existed for each work crew.
- Although not modeled explicitly using the 4D schedule generation software, the superintendents identified a number of locations in the room that could potentially be used for laydown space for equipment prior to installation. In their initial installation sequence developed using the paper isometric drawings, one of the teams of superintendents decided to use the area on the second level as a space to stage equipment for the fire protection system prior to the installation of the air handling units. Using the virtual environment, these areas can be identified, as well.
- The teams of superintendents noted tight tolerances between the supports for the off-module platform and a number of makeup pieces that run underneath. If these pipes were installed prior to the installation of the off-module platform, there is a possibility that they could be damaged during the lift due to the limited space between the anchor point for the platform support and the spool piece. The superintendents noted that it may be possible to install the platform first without the grating section that covers the spool pieces underneath, which could provide better access to the space below. Once the spool pieces were installed and inspected, the grating could be installed.
- Reviewing the installation sequence in the virtual environment led the superintendents to conclude that the air-handling units on the second level should be installed as a single module to reduce the schedule time because of the complexity of the piping and valves attached to the air-handling units. The review of this issue is depicted in Figure 29.

Figure 29: Studying the Air Handling Unit Module

- The superintendents noted that there was insufficient clearance for welding the pipe supports for the fire protection system assembly. They noted that the assembly would be easier to install if it were cut into smaller pieces. The superintendents felt that the field weld locations for the large-bore spool pieces would be difficult to access if the valves on the sample lines were installed as the model showed them. They believed moving the field weld farther away from the elbow would alleviate some of the difficulty. The review of this issue is shown in Figure 30.

Figure 30: Examining the Fire Protection System Piping Assembly

8.2.5.1 Interactive Installation Sequence Development

After the review of the installation sequences they developed using the isometric drawings, the two groups were combined into one and tasked with using the interactive schedule generation tool to develop a sequence for the room. The teams spent less than one hour developing a final sequence using the CAVE. It was clear that the participants applied lessons learned from the activities earlier in the day. The participants mentioned that the CAVE allowed them to recognize additional opportunities for parallel work, which they had not taken advantage of in the schedules they developed using the CAD drawings. In the sequence developed using the CAVE, the teams scheduled two parallel activities initially while the large modules and assemblies were lifted into place. The teams scheduled three teams to perform the makeup piece installation in parallel, which led to a significant savings in schedule time. This breakdown is shown in Figure 31.

Figure 31: Development of Parallel Construction Activities for Room 12306

By collaborating and applying the lessons learned during the development and review of the installation sequence for Room 12306, the final schedule was reduced to 25 days. This represents a reduction of 8 to 12 days or 25 to 30 percent from the sequences developed using the isometric drawings.

8.2.6 Summary of Results

Participants in the experiments noted a number of advantages and disadvantages to using the immersive virtual environment for construction schedule generation and/or review. In addition, the participants from both experiments reported their confidence level before and after using the virtual environment for schedule review. Confidence in the sequences developed either remained the same or improved.

8.2.6.1 Advantages

Based on survey responses, the participants felt that the virtual environment was a beneficial tool for schedule development and review. The participants noted that the VR construction simulation was helpful in determining areas where multiple activities could be performed in parallel. The survey results and the schedule improvement show that the participants were better able to identify constructability issues, design issues, sequencing issues, and space management issues. The participants noted that the virtual environment could also be helpful in determining resource requirements, tool requirements, and material availability during the pre-construction stage of the project.

8.2.6.2 Disadvantages

The participants noted the system cost as the primary disadvantage. In addition, the participants stated that construction professionals would require training to use the system to generate and review schedules. A support staff would be required to maintain the system and translate the 3-D CAD models into a format that can be displayed in the virtual environment.

8.2.6.3 Confidence Level

The participants from both experiments recorded the level of confidence in their installation sequences before and after evaluation in the virtual environment. Five participants reported an increase in confidence after reviewing their installation sequence in the virtual environment, rating their confidence an 8/10 before and 9/10 after. Two participants' confidence level remained unchanged at 9/10. The final participant reported an increase from 9/10 to 10/10, meaning he had full confidence that his schedule was reasonable.

8.2.6.4 Schedule Reduction

Because the graduate students lacked experience in determining the duration of installation activities, an analysis of the reduction in schedule was not possible. A summary of the installation durations from the second experiment is presented in Figure 32. Initially, the two groups of construction superintendents developed construction plans lasting 33 and 36 days. After reviewing the sequence in the virtual environment, they modified some activities that improved constructability but did not remarkably affect the overall construction time. When the teams were combined and they used the interactive sequence development tools, the resulting sequence lasted only 25 days, a significant reduction.

Figure 32: Schedule Time Reduction using Virtual Environment

The improvement in the schedule duration is possibly due to two phenomena; however, with a limited sample set, it is impossible to accurately quantify the contribution of each. The first phenomenon is the effect of collaboration and experienced gained using the virtual environment. The second phenomenon is the enhanced spatial perception achieved by experiencing the yet-to-be-built space in fully immersive 3-D. Being able to “see” the physical size of the space did lead to the planning of additional parallel activities, noted one participant.

9 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 is being created. This dose model allows 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.

9.1 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 5 below:

Table 5: 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
}	

9.2 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 9.1. 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 33.

Figure 33: Flow of Dose Calculation Program

9.2.1 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.

$$\phi(r) = \frac{S}{4\pi r^2} * e^{-\mu_{\text{air}} r}$$

where:

S = source strength in Becquerels (dps or tps)

r = distance from source in centimeters

μ = attenuation coefficient in material (cm^{-1})

9.2.2 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.

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

where:

ϕ = flux in photons/ cm^2 -s

E = Energy in MeV

$\left(\frac{\mu}{\rho} \right)$ = mass absorption coefficient in cm^2 -g

9.2.3 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.

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

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.

9.2.4 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.

$$\dot{X} \left[\frac{R}{hr} \right] = \frac{\phi \left[\frac{\text{photons}}{\text{cm}^2 - s} \right] * E \left[\frac{\text{MeV}}{\text{photon}} \right] * 1.602 \times 10^{-13} \left[\frac{J}{\text{MeV}} \right] * 3600 \left[\frac{s}{hr} \right] * \left(\frac{\mu}{\rho} \right) \left[\frac{\text{cm}^2}{g} \right] * \frac{1000g}{1kg} * 3881 \frac{R}{C}}{\frac{J}{34 \frac{kg}{C}} \frac{kg}{kg}}$$

$$\dot{X} \left[\frac{R}{hr} \right] = 6.57 \times 10^{-5} * \phi \left[\frac{\text{photons}}{\text{cm}^2 - s} \right] * E \left[\frac{\text{MeV}}{\text{photon}} \right] * \left(\frac{\mu}{\rho} \right)$$

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

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 2.58×10^{-4} Coulombs of charge results in the conversion factor.

$$1 \text{ rad} = \frac{100 \text{ erg}}{g \text{ (tissue)}} * \frac{1 \text{ MeV}}{1.60 \times 10^{-6} \text{ erg}} = 6.25 \times 10^7 \text{ MeV} / g$$

$$1R = \frac{2.58 \times 10^{-4} C}{1kg} * \frac{1 \text{ ion pair}}{1.602 \times 10^{-19} C} * \frac{34 \text{ eV}}{1 \text{ ion pair (in air)}} = 5.476 \times 10^{16} \frac{eV}{kg} = 5.47 \times 10^7 \frac{\text{MeV}}{g}$$

$$1R = 5.47 \times 10^7 \frac{\text{MeV}}{g} * 1.60 \times 10^{-6} \frac{\text{erg}}{\text{MeV}} = 87.5 \frac{\text{erg}}{g \text{ (air)}}$$

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

9.2.5 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.

9.2.5.1 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:

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

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:

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

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 34 shows the measured NBS mass-energy absorption coefficient and the function fit to that data used in the dose model calculation.

Figure 34: Comparison of Measured and Calculated Mass-Energy Absorption Coefficient for Air

9.2.5.2 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:

$$\mu_{\text{tissue}} = 4.251514 \times 10^{-3} E^6 - 2.094159 \times 10^{-2} E^5 + 2.935603 \times 10^{-02} E^4 + 8.518912 \times 10^{-03} E^3 - 5.411368 \times 10^{-2} E^2 + 3.931925 \times 10^{-2} E + 2.360246 \times 10^{-2} \quad (6)$$

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:

$$\mu_{\text{tissue}} = 8.38606 \times 10^{-6} E^4 - 2.25563 \times 10^{-4} E^3 + 2.26668 \times 10^{-3} E^2 - 1.08867 \times 10^{-2} E + 3.99109 \times 10^{-2} \quad (7)$$

The use of this function results in errors of 1-percent or less for the entire energy range. Figure 35 shows a plot of the NBS data and the functional fit of the data used in the dose modeling program.

Figure 35: Comparison of Tabular and Functional Fit Values for Mass-Energy Absorption Coefficient for Tissue

9.2.5.3 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:

$$\mu_{\text{air}} = 7.692385 \times 10^{-5} E^{-0.4530147} \quad (8)$$

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 36.

Figure 36: Attenuation Coefficient for Air

9.3 Output

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 37.

Figure 37: Output from Radiation Dose Model

9.3.1 Validation

The radiation dose model was validated by comparing the readings generated by the dose model with the actual readings of a survey meter and a dosimeter. Two Cesium-137 sources, a 46 Curie source and a 70 milliCurie source, were used in the comparison testing. In both cases, the dose model overestimated the actual radiation field and dose received. This is partially due to the dose model simulating an ideal detector. In addition, the source geometry could have varied during the tests, increasing the variability of the actual readings. The data for the validation experiment is reported in the Task 4 final report.

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.

10 Virtual Reality Maintenance Activities

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 38) 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 38: 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 air 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 6 presents the dimensions of the steam drum and the cylinder for the AP 600 and AP 1000 steam generators.

Table 6: 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 4.3. 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 39, were loaded into the virtual mockup.

Figure 39: 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.

11 Application to Gen IV Reactors

Virtual reality technology, applied in the form of full-scale virtual mockups, can help to remove some of the uncertainties associated with the nuclear power plant designs being envisioned for deployment between 2010 and 2020. The ability to navigate through a plant prior to commitment of funding for construction can demonstrate the completeness of the design and perhaps sway investors. The virtual mockup can be used to familiarize personnel with a plant design before, during, and after construction, possibly reducing the steep learning curve for some of the more unconventional plant designs.

The 3D CAD models created by the vendor were successfully imported and viewed in Penn State ARL's CAVE facility, as shown in Figure 40. Three iterations of data transfer were necessary to arrive at a format and resolution that could be easily manipulated. The final version was simplified in the sense that only a single RCS module and a single RSS module were loaded. While the virtual mockup was broken down into eight pieces, it

would be possible to reduce the granularity by further dividing the models in the native CAD system. This would greatly increase the interactivity of the mockup, and it would be necessary to perform installation, maintenance, and constructability studies similar to those performed with AP1000 on the earlier tasks of this research program.

Figure 40: Full-scale Virtual Mockup of PBMR Reactor Cavity

11.1 Potential for Gen IV Design Review

Full-scale virtual mockups show significant promise for next generation nuclear power plant design reviews. The design review in the immersive VR display system is superior to current tools in three aspects – Navigation, 1:1 scale presentation, and 3-Dimensional data display.

Navigation:

The VR system uses a point-and-go motion model that allows the user to point the wand tool in the desired direction, push forward on a thumb-controlled joystick, and move in that direction. The motion model is intuitive enough such that first-time users can pick up the wand and begin navigating the space in minutes. The motion model can either tether the user to the ground similar to walking around the space, or it can be set to allow the user to freely float into spaces that would be impossible to access to gain a different perspective.

1:1 Scale Presentation:

The CAD models created by the designer are presented in full, one-to-one scale to create the virtual mockup. Presenting the data in full scale assists the designer in gaining a true understanding of the size of components being designed, as well as their layout relative to one another.

3-D Presentation:

Data in the CAVE is shown in active stereoscopic 3-D, which reproduces a high-fidelity three-dimensional image by generating two images of each point of view. Images optimized for the left-eye and a right eye are generated at a rate of 96 frames per second – 48 frames for the right eye and 48 frames for the left eye. Special glasses discriminate these frames so that each eye sees the correct image. The active stereo projection gives the user a good sense of depth and a sense of actually being immersed in the space. Qualitatively, the sense of depth provides a more accurate sense of the relative position of objects than looking at 3-D objects on a desktop monitor, or a large screen, for that matter.

The combined effects of the point-and-go navigation model, the 1:1 scale presentation, and 3-D presentation provide the user with an unparalleled experience where design reviews can be performed similar to a walkdown in an operating plant. Systems and equipment can be inspected from the perspective of the workers who will actually be operating the future plant. In addition, because the geometry is computer generated, the user can navigate into spaces that cannot be accessed - through walls, suspended in high locations, in between floors - generating additional benefits and more complete reviews.

The following areas where the virtual mockup could be used in nuclear power plant design review were identified during the initial virtual mockup development task:

- Evaluate Design in full-scale 3D
- Check constructability
- Check for interferences
- Communicate with owner, designer(s), subcontractors, foremen
- Train construction supervision
- Lower number of change orders by spotting potential problems well before the project starts

These same areas should be able to be applied to the Generation IV power plant design.

11.2 Potential for Gen IV Construction Planning

Many of the next-generation nuclear power plant designs, including the GE/Hitachi ABWR, the AECL CANDU-6 and ACR-700, and the Westinghouse AP-600 and AP-1000, are slated to be constructed from prefabricated modules. In order to be economically competitive, the Generation IV reactor technologies will also make use of modular construction techniques.

Modules are typically built off-site in a shipyard or other large-scale manufacturing facility and then transported to the construction site by barge or rail for final assembly. Because of this, the order of installation of the modules and the spool pieces that connect them becomes a concern. The virtual reality system developed during this project provides a method of studying this installation in greater detail than is typically achieved. Installation sequences can be modeled full-scale, in high resolution so that it is possible to view virtual construction. Development of realistic construction schedules and sequences is the key to taking advantage of the benefits offered by modularization.

Modular construction lends itself well to the use of 4-D CAD visualization. 4-D visualization animation capability merges the 3-D CAD geometry of the product model with a construction schedule. The 4-D visualization is typically performed on a desktop computer. The nuclear industry has begun to adopt this technology for the development and planning of construction for Generation III and III+ nuclear power plants. One of the first applications of 4-D construction simulation was performed by Westinghouse in work supported by the Electric Power Research Institute (EPRI). The project involved simulating the first nine months of construction of an AP600 nuclear power plant using industry standard desktop 4-D CAD tools. The simulation was created by linking the Primavera scheduling software to the CAD models created in Intergraph's PDS software. The project demonstrated the usefulness of developing a 4-D CAD representation of nuclear power plant construction. (EPRI, 2000)

The CAVE enables users to evaluate the 4-D representation of construction in full scale. The multi-user room format can allow construction planners to communicate the construction schedule to plant owners, designers, financiers, subcontractors, and foremen. Viewing the space in full-scale 3-D enables better work planning because potential conflicts between trades people working in the same area can be evaluated and laydown spaces can be located. Using the 4-D projection, designers can evaluate issues such as access to confined spaces and access to equipment for welding and cabling. In addition, the 4-D tools presented in the virtual environment enable planners to quickly develop alternative schedules, selecting the shortest most appropriate schedule.

These capabilities are important for the future designer due to the enormous importance of the first-of-a-kind construction to go as planned. Better planning prior to construction can remove some of the uncertainties that may lead to increased confidence that deadlines can be met.

11.3 Potential for Gen IV Maintenance Training

With the deployment of standardized nuclear power plant designs in Generation III (III+) and Generation IV, it may be possible to standardize some training programs. Virtual reality may provide a way to create a flexible whole-plant simulator. Mockups can be created from the 3-D CAD product model and then optimized for operation and maintenance training applications. Work conditions such as noise, radiation, and

radioactive contamination can be simulated to provide a more realistic training experience than the generic mockups that are in use today.

High-risk and high-dose activities are the most common tasks that are practiced on specific mockups. Generic physical mockups tend to be used for the training and reinforcement of good work practices and proper communication between teams of personnel. These mockups can only partially satisfy the need for training on specific pieces of equipment due to their generic nature. Current training practices for Just-in-time (JIT) training and Fix-it-now (FIN) teams focus on table top exercises and training on generic mockups, although these exercises cannot give the workers a true picture of the area where they are to perform their duties. Walkdowns of the area can be beneficial to the maintenance personnel, but sometimes high radiation levels and other hindrances make this difficult or impossible. A full-scale virtual mockup created from the 3-D product model of the standardized plant, such as the one shown in Figure 41, could provide a means of performing all of these activities.

Figure 41: Virtual Reality Maintenance Training

While the two previous areas, design review and construction planning, may be ready for commercial use at this time, the technology's use in operation and maintenance training requires additional research and development. Beyond familiarization training, the current interactivity with the virtual environment would add little to current training applications. The improvement of interaction with the mockup is necessary to facilitate training. For example, the ability to disassemble equipment such as valves or control rod drives would be beneficial. The ability to "operate" valves and other equipment and have the expected feedback such as sound or gauge reading changes would also be advantageous. The improvement of haptics or touch sensing technology would make the experience more convincing to the user. If these capabilities were developed, full-scale

virtual reality mockups could provide a flexible, safe training environment for nuclear power plant applications.

12 Conclusions

Virtual reality technology, applied in the form of full-scale virtual mockups, can help to remove some of the uncertainties associated with the nuclear power plant designs being envisioned for deployment between 2010 and 2020. The ability to navigate through a plant prior to commitment of funding for construction can demonstrate the completeness of the design and perhaps sway investors. The virtual mockup can be used to familiarize personnel with a plant design before, during, and after construction, possibly reducing the steep learning curve for some of the more unconventional plant designs.

The virtual mockup is an excellent tool for design review for a number of reasons. The mockup provides the user with simple navigation using a point-and-go motion model. Geometry is rendered in full-scale, stereoscopic 3-D, which gives users a better sense of scale and depth perception than they can get from a desktop computer system. An independent mock design review performed on Room 12306 in the AP 600 noted a number of items. These items were already recognized by the designer, but the issues stood out when shown in the virtual mockup. A second iteration of the Room 12306 mockup was updated with the design changes.

The virtual mockup was tested as an installation sequence design tool. The mockup enables users to view a 4-D simulation of the construction while being immersed in the geometry, watching the space be built around them. Experienced construction superintendents from Burns and Roe were asked to develop a construction sequence for Room 12306 using isometric drawings provided from Westinghouse. The superintendents visited the CAVE and viewed and optimized the sequence they had developed. Once the superintendents were satisfied with the sequence, they were asked to develop a sequence from scratch using the sequence development capability. The result of the experiment was a significant reduction in planned installation time for the space.

In order to create virtual mockups, the developer should consider the ultimate use of the mockup. If the mockup is to be used for walkthroughs or design reviews, the models can be broken down by system. If the mockup is to be used for modular construction planning, the models should be broken down along module boundaries. If the mockup is to be used for training applications, the models should be divided at the component level or even down to the part level, depending on the desired training application. For example, if the training application is following a procedure, valves and operators should be separated so the user can manipulate the operator.

A radiation dose model was developed to prepare for the performance of a maintenance activity. The dose model calculates the radiation field and radiation dose received by the user while they are immersed in the virtual radiation area. The model calculates the

radiation dose to the user using standard dose versus distance equations in real time. The calculation overestimates the radiation dose received by the user since it models an ideal detector. At this time, the model does not account for shielding from pipes or other obstructions. This capability should be included before the model is used in any production capacity.

A virtual mockup of the steam generator compartment of the AP 1000 nuclear power plant was used to answer two important questions posed by the designer. First, the virtual mockup was used to confirm that adequate laydown space existed for the equipment required to perform sludge lancing, a common PWR maintenance procedure. The second question was whether or not a new tool for sludge lancing would need to be developed due to a change in geometry between the AP 600 and the AP 1000 steam generators. The virtual mockup enabled the designer to stand in the space, assess the available workspace, and, after consultation with the personnel who perform sludge lancing, feel confident that sufficient space existed to perform the maintenance activities.

Two future experiments have been planned that will test the virtual mockups suitability for maintenance training. A radiation protection training activity will be performed using two of the virtual mockups developed during this research program, and an equipment familiarization activity will be evaluated using the virtual mockups. Nuclear engineering students will be trained and assessed using the virtual mockups and the results will be reported in the PhD dissertation of V. Whisker.

In the final task, 3-D CAD data from the PBMR reactor design provided by the designer was converted into a full-scale virtual mockup. A proof-of-principle experiment created a virtual mockup of the reactor cavity showing the maintenance deck, vessel head or “lid shield”, and fuel-handling equipment. The experiment demonstrated that compatible file formats could be determined that allowed the creation of a virtual mockup. The PBMR engineers create models using the Unigraphics suite of design products, a different CAD suite than was previously tested during the collaboration with Westinghouse. The proof-of-principle study determined that using the VRML export feature from the CAD package would be sufficient for creating full-scale virtual mockups of the PBMR reactor design. Since a similar file translation format was used in previous work on the AP1000, it can be assumed that the same tools can be used for the design review, construction planning activities, and the operations and maintenance evaluations.

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 designs because additional input can be solicited from personnel that may not typically be included in the development of construction plans. Having additional users in the space provides the ability to draw on their combined experience, resulting in higher confidence levels.

The benefits of potentially using the virtual mockup can be identified throughout the entire life cycle of the nuclear power plant. During the design phase, different design alternatives can be easily investigated, use of space can be optimized, and disciplines not

typically consulted during design can be included. During construction, scheduling can be developed and optimized, schedule information can be communicated, and space considerations can be evaluated. The virtual mockup can potentially be used for orientation, simulated maintenance, procedure development, and training during the operation and maintenance phase.

In summary, the results of this project demonstrate that full-scale virtual mockups presented in a CAVE can be used today as an effective tool for design review of commercial nuclear power plants. The technology is also ready to play a limited role in construction/constructability analyses of next-generation nuclear power plants. Additional development and testing are required before the virtual mockup technology can be used for nuclear power operation and maintenance applications.

13 References

Electric Power Research Institute. "Virtual Construction: Linking the 3-D Model of the AP600 Nuclear Plant Design to its Construction Schedule," EPRI, Palo Alto, CA. 0000000000001000149. (2000)

Tatum, S.A., Byrum, J.C., Rourke, P.W. "Design Validation Using Computer Models in Lieu of Full-Scale Mockups." *Marine Technology*. **31**:3:, pp. 225-230. (July 1994)

14 Publications from this Research Program

14.1 Papers

Generation IV Construction Cost Reductions Using Virtual Environments, A. J. Baratta, V. E. Whisker, S. C. Mouli, S. A. Shaulis, T. S. Shaw, M. E. Warren (Penn State), J. W. Winters, J. A. Clelland (Westinghouse), VOLUME 86 TANSO 86 40, (2002).

Modular Construction Installation Study using Virtual Environments, V. E. Whisker, A. J. Baratta, S. C. Mouli, T. S. Shaw, M. E. Warren (Penn State), J. W. Winters, J. A. Clelland (Westinghouse) VOLUME 87 TANSO, (2002).

Using Immersive Virtual Environments to Develop and Visualize Construction Schedules for Advanced Nuclear Power Plants, V. E. Whisker, A.J. Baratta, S. Yerrapathruni, J.I. Messner, T. S. Shaw, M.E. Warren, E.S. Rothhoff (Penn State), J. W. Winters, J. A. Clelland, F.T. Johnson (Westinghouse) Proceedings ICAPP 03 (2003)

Using Virtual Reality to Improve Construction Engineering Education. J.I. Messner, S. Yerrapathruni, A.J. Baratta, and V.E. Whisker. 2003 ASEE Annual Conference, Nashville, TN. (2003)

Experimental Results from a Modular Installation Sequence Study using Virtual Environments, V. E. Whisker, A.J. Baratta, S. Yerrapathruni, J.I. Messner, T. S. Shaw, M.E. Warren, E.S. Rothhoff (Penn State), J. W. Winters, J. A. Clelland, F.T. Johnson (Westinghouse) VOLUME 89 TANSO 89 58-59 (2003).

Development of a Radiation Dose Model for Immersive Virtual Environments, V.E. Whisker, M.E. Warren, A.J. Baratta, T.S. Shaw. VOLUME 89 TANSO 89 56-57 (2003).

Immersive Virtual Reality Applications at Penn State: Development of the Virtual AP1000 Nuclear Power Plant. V.E. Whisker, A.J. Baratta, T.S. Shaw. Proceedings of the Fourth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control, and Human-Machine Interface Technologies (NPIC/HMIT) American Nuclear Society (2004).

14.2 Theses

Yerrapathruni, S.C.M.. "Using 4-D CAD and Immersive Virtual Environments to Improve Construction Planning." MS Thesis, The Pennsylvania State University. (2003)

Whisker, V.E. "Using Immersive Virtual Reality for Nuclear Power Plant Training Applications." PhD Dissertation, The Pennsylvania State University. (2006, anticipated)

14.3 Other Press

Westinghouse World View, December 2004, pp. 6-8

Power Magazine, May 2004, pp. 59-62, www.powermag.platts.com

Insight Magazine, Q1 2004, <http://ppo.intergraph.com/insight/5-1/4-taw.asp>

Nucleonics Week, 22 May 2003, pp 14-15.