Abstract – Ongoing research aims to determine if a full-scale virtual reality mockup can be effectively used to reduce construction and maintenance costs of the next generation of nuclear power plants. A full-scale virtual mockup of Room 12306 of the Westinghouse AP1000 nuclear power plant provides the test bed for this research. Located in the auxiliary building, Room 12306 contains a number of construction modules and assemblies comprised of piping from 10 different fluid systems.

The virtual mockup developed at Penn State is currently being evaluated for visualizing and testing the planned construction of Room 12306. Using the virtual mockup, the designer and contractor can evaluate, in 1:1 scale, a step-by-step installation sequence for the modules and piping assemblies for completeness and feasibility. Simulating a multiple-step installation sequence, the user can experience a human-in-the-loop, virtual construction of the yet-to-be-built space. Using software tools, the user may also interactively develop installation sequences by selecting modules and assemblies in the appropriate order.

Two sets of experiments performed at Penn State ARL’s SEALab were used to determine the value added by using the virtual mockup to develop and visualize the construction schedule for Room12306. During the first experiment, two groups of Penn State construction management students were asked to use the virtual mockup and associated software tools to develop a construction sequence for Room12306 without any prior knowledge of the space. The groups were able to easily identify constructability issues and find opportunities for scheduling parallel activities, although they had no prior experience with the room. The second experiment asked two teams of experienced construction superintendents to develop a construction schedule for the space using drawings provided by the designer. The teams viewed and evaluated the schedules they developed in the virtual mockup. The teams used knowledge gained from this evaluation to develop an optimum schedule in the virtual mockup. The optimum schedule balanced the workload across three crews, resulting in a significant reduction in estimated construction time.
nuclear energy sources. Current estimates for the advanced reactors such as the AP600 are in the neighborhood of $1300/kilowatt for the nth plant. This cost is about 30% higher than the $1000/kilowatt target, generally considered necessary for nuclear to be competitive with fossil sources.

Efforts to reduce costs beyond those of the AP600 have resulted in the design of generation III+ and IV reactors. Such reactors include the AP1000, a generation III+ reactor and the pebble bed modular reactor, a generation IV reactor. For the AP1000, the costs for the nth plant are estimated to be less than $1000/kilowatt. There is still some uncertainty that this cost can be realized for these plants, since a plant of this design has not yet been built. Construction costs of nuclear generating plants must be reduced in order to expand the future use of nuclear energy.

Two of the primary drivers of plant cost are the cost of financing and the cost of skilled labor during the planned construction schedule. If the construction schedule can be reduced, the cost of construction will, in turn, be lowered.

In the nuclear industry, many vendors are turning to 3-D and 4-D CAD tools to assist them in optimizing construction schedules and developing modularization techniques. While these tools are beneficial, additional improvement can be gained by displaying and developing schedules using 4-D CAD displayed using immersive virtual reality.

II. IMMERSIVE VIRTUAL REALITY TECHNOLOGY

Full-scale immersive virtual reality technology, perhaps better known as CAVE™ technology, has been in development for about 10 years. A number of footprints are now available. The SEALab at Penn State ARL utilizes a Surround Screen Virtual Reality (SSVR) system, developed by Mechdyne. The SSVR is a CAVE-like immersive projection display (IPD), which may be used to view three-dimensional stereo images and simulations in actual one-to-one scale. Projectors behind the screens project alternating images optimized for the left and right eyes, generating a 3D stereoscopic image. While the traditional format of the CAVE™ system is three walls and a floor, the SEALab system has four walls, completely surrounding the user with an image. A schematic of the SEALab’s IPD system appears in Figure 1.

A number of tools facilitate interaction between the user and the computer-generated image in the IPD. A speech-to-text algorithm recognizes voice commands given by the user. A motion tracking system tracks the movements of the user and a number of implements within the environment. The motion tracking system allows the computer to adjust the displayed image to be optimized to the viewer’s eye point. This system tracks the location of a three-dimensional mouse-like navigation tool, as well as a glove worn by the user. The mouse-like device allows the user to navigate freely and intuitively within the virtual environment using a joystick/trackball controlled by the thumb. To interact with the image, the user wears a glove with touch sensors on each fingertip. Using software, each pinch gesture may be tied to an activity such as grabbing objects, using a measuring tape, or moving equipment within the virtual environment. The glove also serves as a pointer used to identify or select equipment. Finally, the user wears a pair of liquid crystal display (LCD) shutter glasses to view the 3D images generated by the computer. The voice command recognition system, motion tracking system, the 3-D mouse, the pinch glove, and the shutter glasses, shown in Figure 2, provide the user with an interactive, immersive virtual reality experience.

III. VIRTUAL MOCKUP DEVELOPMENT

Immersive virtual reality technology was used to develop a virtual mockup of a space in the AP1000 nuclear power plant design. Mockups, both full-scale and reduced-scale, are used in many industries, including the nuclear power industry, for orientation and training. The scale of a nuclear power plant precludes the development of complete full-scale mockups. Reduced-scale mockups are expensive and often lack sufficient detail to be useful since not all piping may be represented. For example, the US DOE commissioned a scale model of the AP600 nuclear power plant, which cost approximately $600,000. Although the model had many dynamic features, only large equipment was modeled. Many times, resources are not available to construct task-specific physical mockups for any activities except those that are high risk. The virtual mockup was designed to be a practical, economic means of performing orientations, design reviews, layout studies, and ergonomic studies.

The virtual mockup was created by exporting the 3D CAD models into a format recognized by the IPD system, where they could be displayed in one-to-one scale. The current process used to translate the CAD models to create the virtual mockup is depicted in Figure 3. Three-dimensional CAD models are first exported to virtual reality modeling language (VRML), a format for constructing and viewing 3D models. Next, a few lines are changed in the VRML file to make the models compatible for viewing in the IPD. Finally, the files, generated around a common origin, are linked together to form a scene.
The 3D CAD models received from the designer, used to create the virtual mockup, typically contain pipes, valves, or equipment from a single fluid system. Depending on the desired use of the virtual mockup, the systems or equipment may be subdivided into smaller parts using a compatible 3D CAD program. There are a number of possibilities for subdividing the 3D CAD models for display. If the mockup is to be used for spatial orientation, VRML models that contain the pipes, valves, and equipment from a specific system are sufficient. This allows the systems to be readily identified.

If the mockup is to be used for maintenance simulation or other training applications, additional interaction is required so the system-level models are subdivided to the individual component-level. The 3D CAD models are divided such that each pipe section and valve is modeled in a separate VRML file. These smaller, finely resolved parts can be manipulated, moved, and identified. For example, because the designer used high-resolution valve models composed of multiple pieces, the operator or hand wheel can be separated from the body of the valve, potentially allowing the user to virtually operate the valve.

IV. VIEWING AND DEVELOPING SCHEDULES USING THE VIRTUAL MOCKUP

The Westinghouse AP1000 nuclear power plant is designed to be constructed using prefabricated modules, which are built off-site in a shipyard or other large-scale manufacturing facility and are transported to the construction site by barge or rail. Modular construction is designed to increase the quality of workmanship as well as to speed construction. The plant is assembled using an open-top construction technique, where the modules are lifted into place through the open roof using a crane. When using modular construction, the order of installation of the modules and the connecting (spool) pieces is of primary concern during the schedule development process. Development of realistic schedules is the key to taking advantage of the benefits offered by modularization.

IV.A. Viewing Completed Construction Schedules

Previous studies have shown that 4D-modeling techniques, which assign 3D CAD objects to a corresponding schedule activity, can improve the project planning process by providing the construction planners with the opportunity to visualize and communicate the construction schedule.\textsuperscript{6,7} Currently, 4-D models are created and viewed using desktop schedule simulation software. The research described here aims to extend this concept of the 4-D model by allowing a user to view the space being constructed in full one-to-one scale.

The schedule simulation software allows the user to link CAD models to schedule activities creating 4-D model. The 4-D models of the construction schedule can be animated once the linking is complete. 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 by the current software is an effective method of tracking progress throughout the construction sequence.

The functionality offered by the desktop visualization software has been mimicked for the IPD 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 IPD 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, loaded at the same time as the geometry, controls the animation of the installation sequence. The user inputs the start time and end time for each activity, as well as the name of the object being installed at that time. This feature allows concurrent activities to be scheduled and visualized accordingly. If desired, the user may input module names rather than individual object names.

Once the configuration file has been completed, the schedule may be visualized in the IPD system. After issuing the ANIMATE command, users may then stand in the IPD and watch the space be constructed around them. As the pieces are installed, the text-to-speech software announces the object name or module name of the piece currently being installed to assist the user with orientation. Once the playback of the installation sequence has been completed, the user can restart the sequence using the RESTART command and then advance through the schedule step-by-step using FORWARD and BACKWARD commands. The FORWARD and BACKWARD commands allow the user to examine fine details, which 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 re-evaluated.
IV.B. Schedule Development Tools

In order to make creation of realistic schedules easier, a number of interactive tools have been developed for use in the IPD. First, the user may query the part name or object name using the IDENTIFY function. Second, the user may point at an object and select it using 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 4 depicts views of piping before and after selection.

In order to view the sequence, the user must program 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 scripted to speed the schedule development process.

V. EXPERIMENT DESCRIPTION

Using current schedule visualization methods, the schedule reliability and confidence achieved by planners during the initial phase of a complex project is limited. There is a need for tools that assist project planners in achieving such reliability and confidence. One method that is currently being researched is the use of immersive virtual reality technology. The potential for the use of the Immersive Projection Display (IPD) as a tool to visualize a 4D construction simulation at a one-to-one scale lacks measured evidence for proper justification of the additional “value-added” (in terms of confidence achieved) by this tool. Because of the lack of measured evidence, two experiments have been developed to investigate the application of CAVE-like Immersive Projection Displays for improving the schedule reliability and confidence of project planners before beginning construction.

The first experiment was designed to be a proof-of-principle test to evaluate new functionality developed to allow construction superintendents or similar trades people to interactively create installation sequences. The experiment was tested using graduate students in construction management from Penn State. The subjects had no prior knowledge of the plant design or the specific area represented by the virtual mockup. After a brief introduction to the mockup and the modules within Room 12306, the participants were asked to develop an installation sequence for the modules and the makeup pieces using the interactive tools in the virtual mockup. The results of the first experiment were primarily qualitative observations aimed at improving the second experiment.

The second experiment investigated the application of the immersive virtual reality technology to improve schedule reliability/confidence of project teams. In addition, the experiment was designed to test a method of applying the IPD technology to the current schedule development workflow. Participants also interactively developed an installation sequence in the IPD, similar to the procedure developed for the first experiment.

Two teams, each consisting of two experienced construction superintendents provided by Burns and Roe, were provided with 3D drawings of the modules, assemblies, and makeup pieces from Room 12306. Each team was asked to develop 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 allowed two days for the schedule development. Once the schedules were generated, each team was surveyed to evaluate their level of confidence in the construction plan. The construction plan generated by each team was sent to Penn State and displayed in the CAVE-like IPD. The teams visited the SEALab at Penn State ARL where they viewed and analyzed the construction plans they had developed. 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 CAVE-like IPD. 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 results of the experiments were analyzed by performing a content analysis of the surveys and by recording anecdotal information. The results of each experiment are presented in the following section.

VI. EXPERIMENTAL RESULTS

The results of each experiment are discussed below.

VI.A. Experiment 1 Results

After a tour of the layout of the mockup testbed, the participants began to develop the installation sequence for the space. Each team presented a clear strategy for their
work plan; however, each of the teams developed a unique sequence.

Sequence development using the tools in the IPD took less than one hour. The sequence was played back and critiqued by the users. 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.

Standing in the room before and during construction fostered discussion of the actual methods of construction that would be used. The subjects discussed the use of spreader beams for lifting pipes into place. They also mentioned module size limitations and accessibility issues for some of the field weld locations. The enhanced spatial perception offered by the virtual reality system allowed the students to take workspace interference between trades into account while they planned a number of parallel activities. Using the immersive schedule development software, the subjects were able to develop a reasonable installation sequence with no prior introduction to the space and little experience in nuclear power plant construction.

The participants rated the development of installation sequences using the virtual mockup an average of 9 out of 10 in ease of use. One participant, an experienced project engineer, noted that the IPD was extremely helpful in gaining a clear understanding of a project in much less time than blueprints or even 3D models. The participants rated their confidence in the schedule they had developed an 8 out of 10.

As expected, the first experiment exposed some shortfalls in the strategy and execution planned for the second experiment. The subjects mentioned 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.

As a result of lessons learned from the first experiment, a number of changes were made to the mockup to accommodate necessary refinements to the granularity of the schedule activities. Prior to the first experiment, a number of refinements were made to the original models received from the designer, in order to facilitate the model’s use for installation simulations. Originally, the mockup was comprised of 9 steps, 7 assemblies, 5 sets of makeup pieces, and a total of 40 model objects. Since the five sets of makeup pieces were insufficient for developing a realistic installation sequence, 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 3D CAD drawings were received from the designer. After the refinements, up to 51 steps, 6 or 7 assemblies, 45 makeup pieces, and 75 model objects were available to the construction planner.

VI.B. Experiment 2 Results

Two groups of experienced construction superintendents participated in the second experiment. After spending less than one day reviewing the 3D CAD drawings provided by the designer, the teams each developed a construction schedule for Room 12306. Penn State received the two construction schedules for conversion to a format that could be displayed in the IPD. One team documented the schedule in Excel with activities broken down by man-hours, while the other team created the schedule using Primavera and allowed one day for each activity. Each schedule activity was matched to an object model for use in the IPD. The time scale in the configuration file was scaled to match the length of time the teams allotted for each activity.

Each team viewed their sequence in the IPD 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.

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 a platform, which supports four air-operated valves and two four-inch pipes. Using the 3D CAD drawings provided, it was unclear that four makeup pieces of varying diameters pass underneath of 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 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.

After the review, 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 IPD. It was clear that the participants applied lessons learned from the activities earlier in the day. The participants mentioned that the IPD 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 IPD, 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. The schedule review is shown in Figure 5.

A comparison of the schedule duration between the conventional method using the 3D CAD drawings and the interactive method using the IPD is shown in Figure 6. The construction sequence developed using the interactive method lasted 35 days. The sequences developed using the CAD drawings had durations of 48 days and 53 days. The interactive method resulted in schedule savings of 27-percent and 33-percent, respectively.

Based on the initial findings of this research, additional trials of the experiment are warranted to determine if this significant reduction in schedule is a result of the combined experience of the subjects or if it is due to the enhanced sense of spatial perception offered by the IPD system. The sample set analyzed is not large enough to make any definitive determination of the level of improvement; however, a measurable improvement in the schedule was observed. The reduction in schedule time and increase in confidence demonstrate this.

VII. PROPOSED BENEFITS

Using this immersive form of 4D CAD, a number of benefits are expected. First, the development of improved construction sequences will lead to reduced project duration. Because of the better sense of spatial perception offered by the virtual reality system, temporary interferences, installation paths, and workforce congestion or interferences between trades can be better characterized. The large format display and animation capability offered by the IPD system facilitates the communication of the schedule to team members, trades people, and foremen. The ability to include additional experienced personnel in the scheduling process, such as foreman or construction personnel, leads to improved schedules. Effective review and communication of the schedule are necessary to generate investor confidence in the constructor’s ability to actually build the plant.

VIII. CONCLUSIONS

Immersive virtual reality technology is currently being investigated as a means of reducing cost and schedule time for future nuclear power plant designs. Ongoing research at Penn State is investigating the development and use of virtual reality mockups for design review, schedule development, and personnel training. Two experiments, developed to test the use of the virtual mockup for installation sequence development and visualization, have yielded promising results, with one test showing an approximately 25-percent reduction in schedule time over traditional schedule development methods. The scope of the experiment should be expanded to include additional teams of experienced construction personnel to generate additional data to allow a definitive determination of the value of using immersive display technology in construction planning.

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NOMENCLATURE

CAD – Computer Aided Design
CAVE – CAVE Automatic Virtual Environment
IPD – Immersive Projection Display
SSVR – Surround Screen Virtual Reality
VRML – Virtual Reality Modeling Language

REFERENCES

Figure 4: Demonstration of the SELECT Function

Figure 5: Interactive Development of an Installation Sequence

Figure 6: Comparison of Planned Construction Time using Conventional and Interactive Scheduling