



## **Nuclear Energy Research Initiative**

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

#### **Task 5 Completion Report: Generation IV Reactor Virtual Mockup Proof-of-Principle Study**

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## EXECUTIVE SUMMARY

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

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

The objective of this 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.

Much of the development of the virtual mockup has taken place at Penn State ARL's SEA Lab facility. The SEA Lab equipment includes a 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. This device also facilitates interaction with objects within the image. Together these tools provide the user with a believable virtual reality experience.

A full-scale virtual mockup of the reactor cavity of the Pebble Bed Modular Reactor (PBMR) has been developed. To create the virtual mockup, three-dimensional CAD models of the PBMR reactor cavity provided by the designer were translated into a format that can be viewed in a CAVE. Once the models are loaded into the CAVE, many human-centered activities, such as navigation, orientation, and object identification and manipulation, can be evaluated in full one-to-one scale.

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## **1 Introduction**

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

## **2 Task Description**

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

Task 5 includes the following activities:

- Investigation of the feasibility of incorporating 3D CAD models from a Generation IV nuclear power plant, most likely the Pebble Bed Modular Gas-cooled Reactor (PBMR)
- Determination of the feasibility of performing similar installation sequencing and maintenance studies using a virtual mock-up of the Gen IV reactor

## **3 Generation IV Reactor Designs**

Generation IV reactor designs encompass many new nuclear power plant designs which offer advantages over the current generation of plants in the areas of economics, safety and reliability, and sustainability. These plants could be deployed commercially by 2030.

According to the US DOE, “Concerns over energy resource availability, climate change, air quality, and energy security suggest an important role for nuclear power in future energy supplies. While the current Generation II and III nuclear power plant designs

provide an economically, technically, and publicly acceptable electricity supply in many markets, further advances in nuclear energy system design can broaden the opportunities for the use of nuclear energy.” (DOE, 2005)

Six categories of nuclear power plants were selected for further study under this program in 2002. (DOE-INEEL, 2005) They are:

- Gas-Cooled Fast Reactor
- Very-High-Temperature Reactor
- Supercritical Water Cooled Reactor
- Sodium-Cooled Fast Reactor
- Lead-Cooled Fast Reactor
- Molten Salt Reactor

The Pebble Bed Modular Reactor design, selected for this feasibility study, would fall under the Very-High-Temperature Reactor designation.

## **4 Immersive Virtual Reality Display Systems**

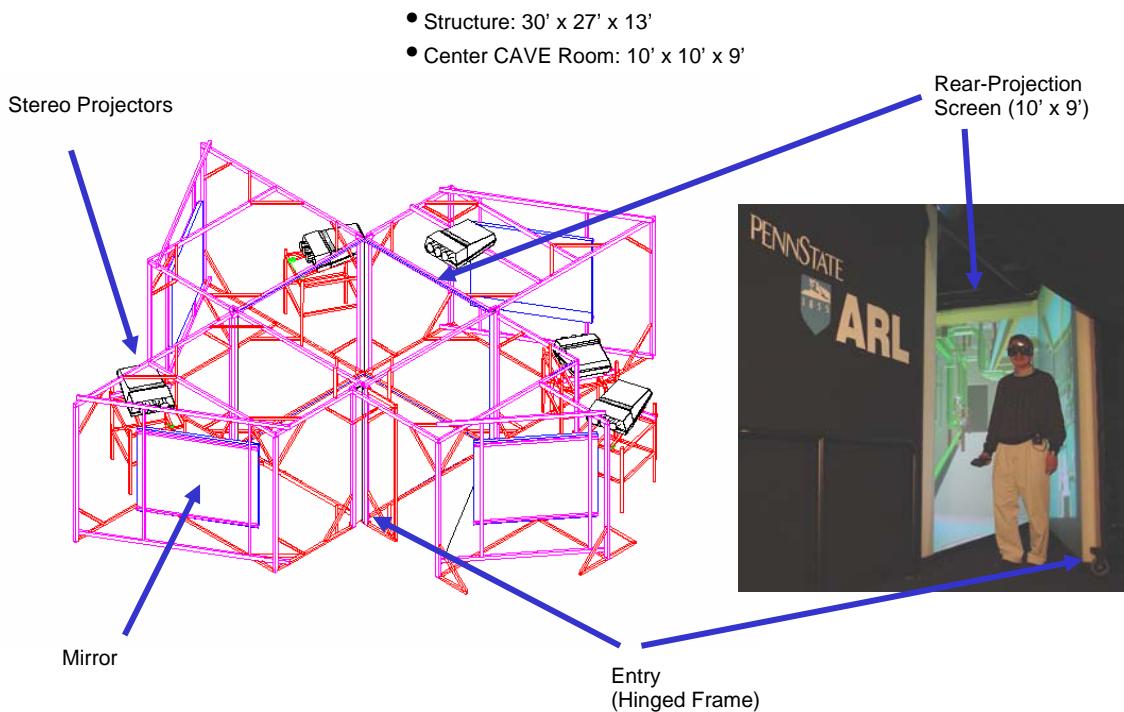
Many universities and laboratories have access to some sort of virtual reality system - a CAVE, ImmersaDesk, Power Wall, head-mounted display, or some home-grown solution. These VR solutions provide different qualities of VR experiences, depending on many factors such as whether or not they are coupled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

### **4.1 Penn State ARL's CAVE System Components**

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

SEA Lab's CAVE was designed and installed by Mechdyne Corporation. The Surround Screen Virtual Reality (SSVR) system is a turnkey virtual reality platform, which includes the display, the projectors, and all of the required hardware. A 22-processor Silicon Graphics Onyx4 computer serves as the image generator. The computer uses 10 separate graphics processors that render each eye for the five screens. The left eye and right eye images are interlaced using an external box called a compositor. A High-

Bandwidth BarcoGraphics CRT projector projects the image generated by the computer on to a Mylar mirror, which reflects the image onto the back of each of the four wall screens. Penn State ARL has custom built CAVE system with four walls that surround the user as well as a top-projected floor. A diagram of the Penn State ARL CAVE is shown in Figure 1.



**Figure 1: PSU ARL Immersive Projection Display System**

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



**Figure 2: Active Stereo LCD Shutter Glasses**

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

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

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



**Figure 3: MiniTrax Wand**

## **5 Creating Full-Scale Virtual Mockups**

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

## 5.1 Why Create A Virtual Mockup?

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

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

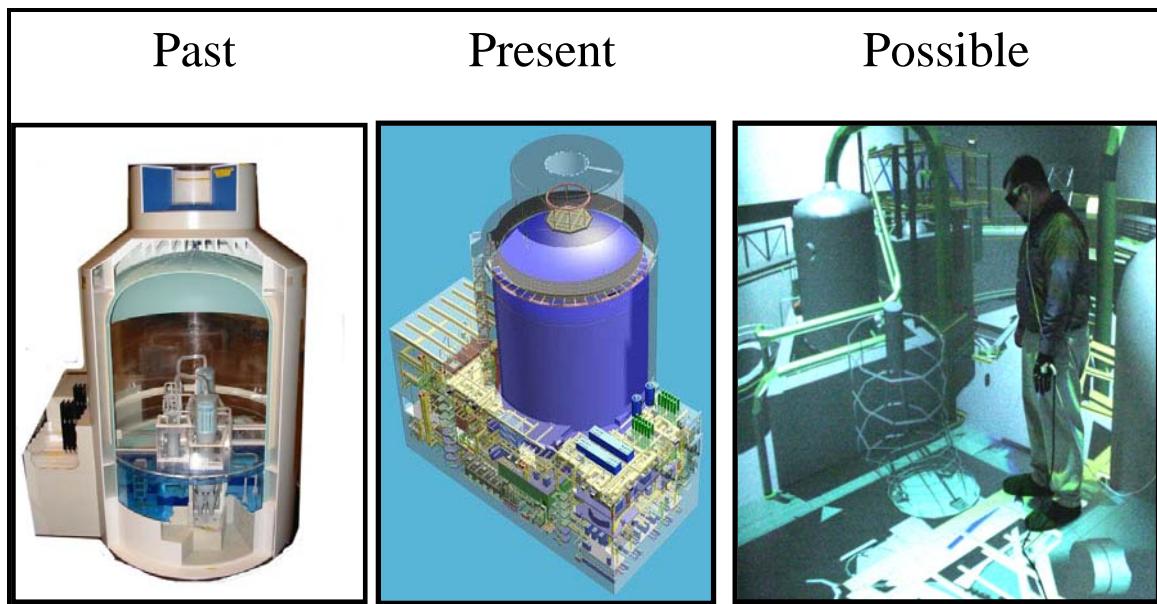


Figure 4: Design Review: Past, Present, Future? (l to r)

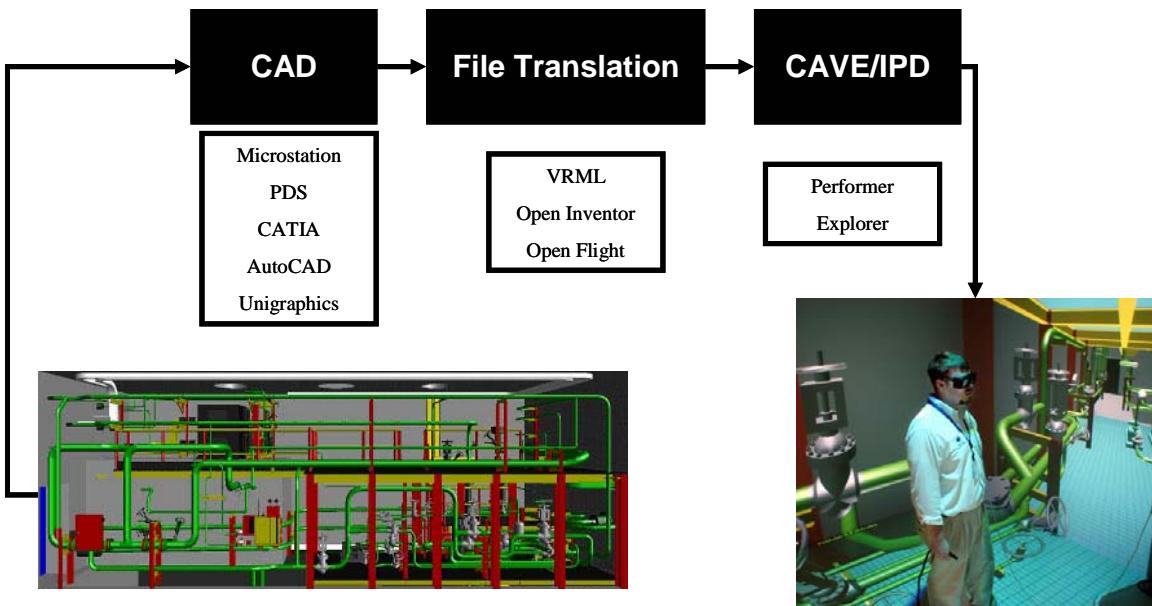
Full-scale virtual mockups have a number of advantages and one significant drawback. These mockups, presented in a CAVE display system, are freely and easily navigated. The virtual mockups created for this project utilize a “point-and-go” model in which the user need only to point in the direction he wishes to travel and push forward on the joystick on the wand to navigate the mockup. The user has the option of clamping to the ground with simulated gravity or flying around, gaining a different perspective. In addition to intuitive navigation, the virtual mockup provides the user with a full-scale,

one-to-one, representation of the geometry. Actually being immersed in the space gives the user a truer sense of scale than that provided by a desktop display. Displaying the data in a stereoscopic environment provides the user with an accurate sense of depth and relative size of equipment. There is, however, one drawback to this technology. It is expensive. A CAVE system similar to the one at Penn State ARL's SEA Lab can cost nearly two million dollars, although multiple mockups can be created and displayed on the system.

## 5.2 Creating Full-scale Virtual Mockups from CAD Models

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

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



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

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.

## **6 Creation of a PBMR Virtual Mockup**

### **6.1 PBMR Virtual Mockup Development**

Designers in many industries use 3-D CAD packages to develop their designs. The virtual mockup developed during this research program takes 3-D CAD one step further, presenting it full-size at one-to-one scale within a human-centered virtual environment. The CAD package chosen by the designer, PBMR, Pty., is capable of exporting a file format that can, with effective geometry translation, be viewed and interacted with in a CAVE or similar Immersive Projection Display (IPD) system.

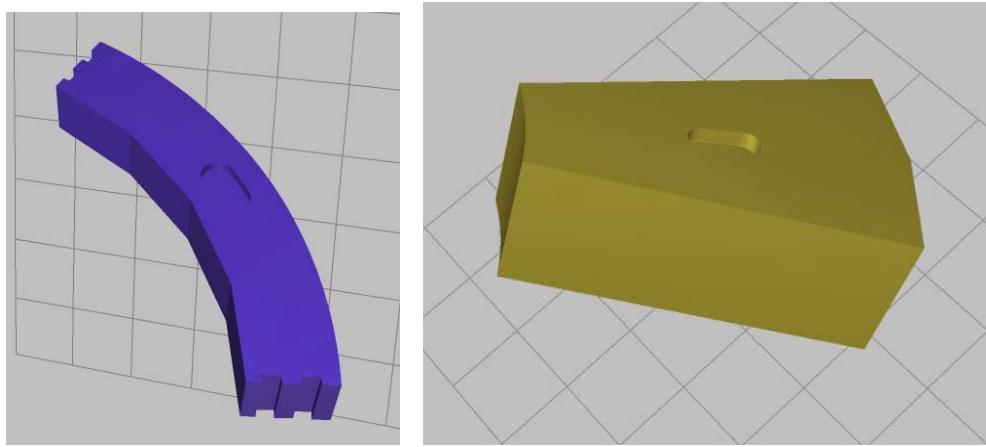
The PBMR design has been modeled by the designer in another CAD software suite, Unigraphics NX. Penn State initially did not have any tools to work with the models in their native format; however, tools to read and convert many of the CAD formats exist and can be located on the Internet. It is also possible to obtain evaluation software licenses for the CAD packages. One such license was obtained for Unigraphics Solid Edge, although this package was unable to read the files Penn State received from PBMR. A demonstration version of AutoVue from Cimmetry Systems ([www.cimmetry.com](http://www.cimmetry.com)) was downloaded from the Internet. This software enabled Penn State to view and convert some of the PBMR files, namely those files sent in Unigraphics \*.jt format.

### **6.2 Data Transfer**

Three transfers of data between PBMR and Penn State occurred. These transfers are described below.

#### **6.2.1 Revision 1**

The first set of data received by Penn State contained two models in Unigraphics native format (\*.jt). These two models were designed to test the data transmission protocol and file conversion tools. The files, 013649\_\_SOLID.jt and 013650\_\_SOLID.jt, were successfully converted to VRML using the AutoVue software discussed above. These files are shown in Figure 6.

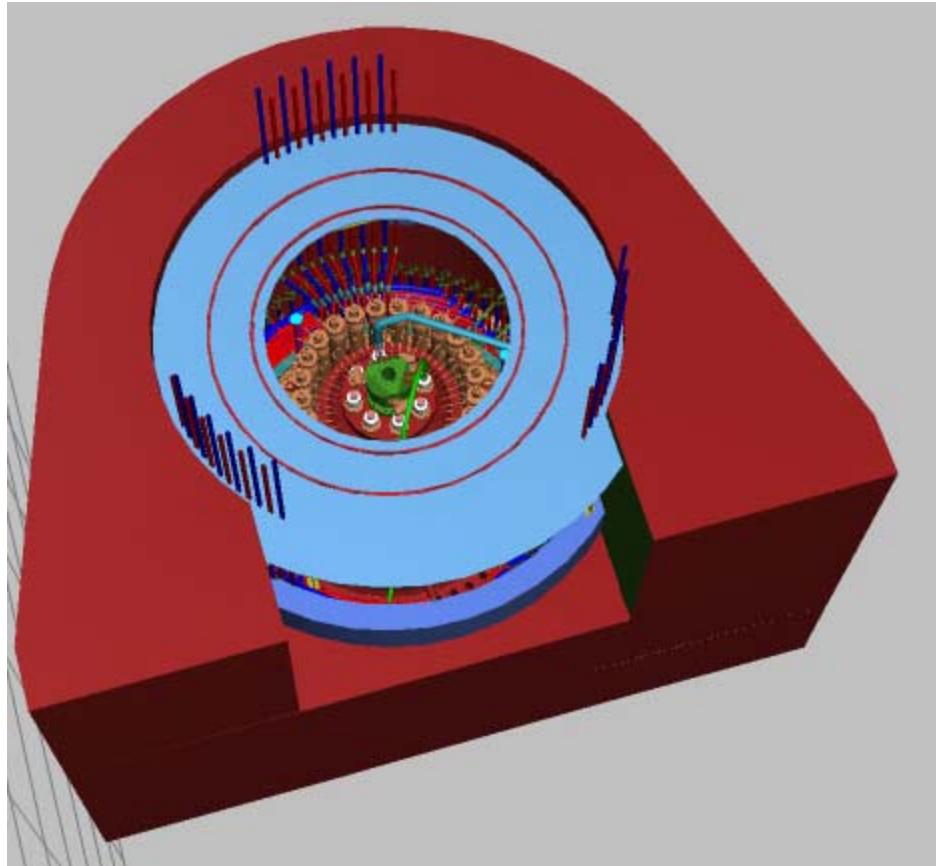


**Figure 6: PBMR Test Models (\*.jt format)**

### 6.2.2 Revision 2

The second data transfer took place once the test models had been successfully viewed. Three versions of the PBMR reactor cavity geometry were placed on a secure FTP site for Penn State to download. The models on the FTP site were 023580\_RC\_TOP\_1.wrl, 023580\_RC\_TOP\_1.x\_t, and 023580\_RC\_TOP\_1.prt in VRML, Parasolid, and Unigraphics formats, respectively. Unfortunately, the reactor cavity was delivered as a single file, causing all of the models to be quite large: the VRML file was approximately 130 MB, the Parasolid file was 124 MB, and the Unigraphics file was 187 MB.

Because the files were so large, they proved to be difficult to work with. Without direct access to a Unigraphics software suite, the Parasolid file and the Unigraphics file could not be manipulated. Typically, file translation software can be used to effectively change file formats, but the large file size eliminated translation as an option. It was, however, possible to view the VRML file using desktop tools such as Right Hemisphere's Deep Exploration ([www.righthemisphere.com](http://www.righthemisphere.com)), as shown below in Figure 7. The model translated into more than 1.1 million polygons. Because of the model's complexity, it failed to load in the CAVE because its size exceeds the 32-bit application's addressable memory limitation of approximately 1 GB. Another solution was sought to render the reactor cavity.



**Figure 7: Complete PBMR Reactor Cavity VRML Model Shown in Deep Exploration Software**

#### 6.2.3 Revision 3

A third transmission of data was completed after the large models proved to be unworkable. This data set contained eight new VRML models:

023580\_RSS\_1OFF.wrl  
023580\_RCS\_1OFF.wrl  
023580\_MAINTENANCE\_FLR.wrl  
023580\_LID\_SHIELD.wrl

023580\_FHSS.wrl:  
The FHSS has the following functions:

loading fresh fuel into the reactor;  
removing spent fuel from the reactor;  
storing spent fuel within the module until the plant is decommissioned  
circulating the fuel spheres through the reactor for multi-pass burn-up  
loading the core in such a manner that the two-zone core is maintained.

023580\_CITADEL\_BLDG.wrl

023580\_RCCS.wrl  
023580\_RSS\_BODY.wrl.

These models were converted for viewing in the CAVE, and an application definition file (ADF) was created to merge the models into a scene. The ADF contains all of the model objects and ties them to a common origin, creating the virtual mockup. The simplified mockup of the PBMR reactor cavity is shown in Figure 8. The relative simplicity of the model can be seen when compared to the full version shown in Figure 7, although the viewpoint is slightly different.

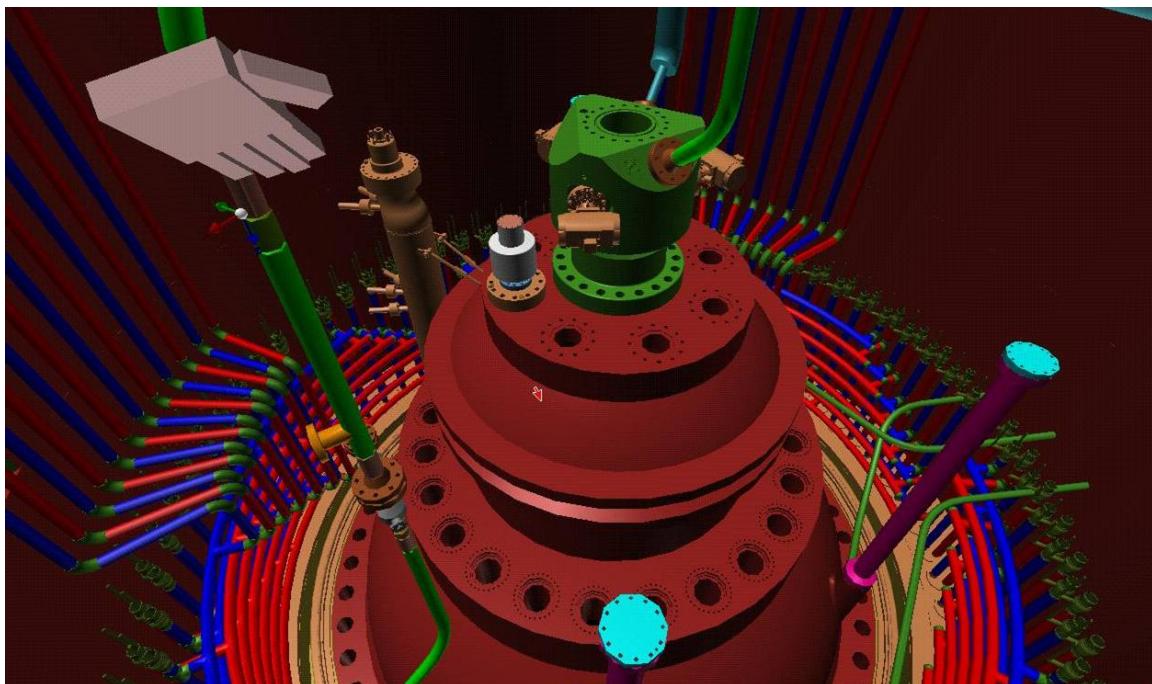
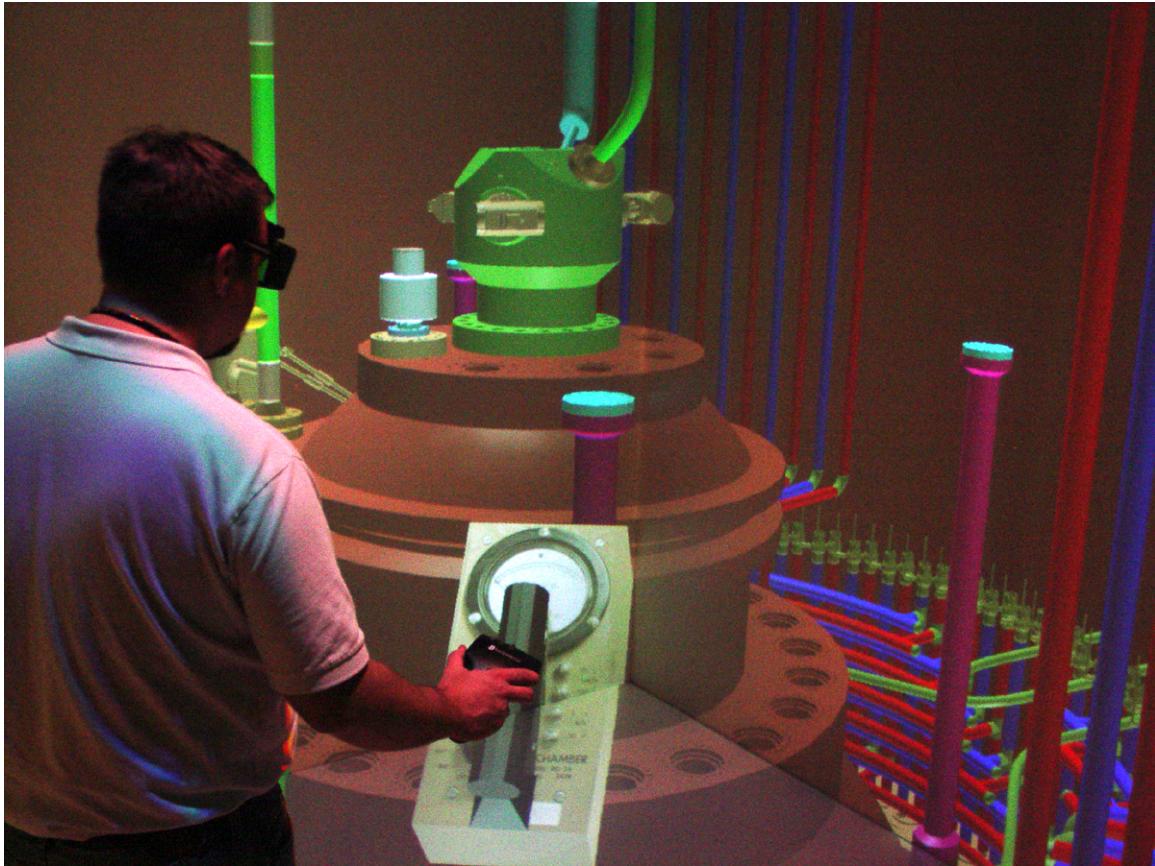


Figure 8: Top View of PBMR Reactor Cavity from Explorer Desktop View

## 7 Summary of Results

The 3D CAD models created by the vendor were successfully imported and viewed in Penn State ARL's CAVE facility, as shown in Figure 9. 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 9: Full-scale Virtual Mockup of PBMR Reactor Cavity**

## 7.1 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.

## 7.2 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.

### 7.3 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 10, could provide a means of performing all of these activities.



**Figure 10: 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.

## **8 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.

In this 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.

## **9 Opportunities for Further Research**

The research presented in this report lays the groundwork for the creation of full-scale virtual mockups presented in a CAVE system for Generation IV nuclear power plant designs. While the design review and construction planning tools could be used in their present form, further optimization of the tools for the specific Gen IV data set would be

recommended. The 4-D construction visualization capability can be further improved to animate and evaluate the actual construction of the modules used to construct the power plant. Equipment installation and removal paths could be evaluated in full-scale 3-D, which would increase the planner's confidence level that the task could actually be performed.

The maintenance planning and procedure optimization tools require significant work in order to be deployed for production-level efforts. Significant improvement in the interactivity with the model is required to create a believable training environment. The ability to "operate" valves and other equipment, generating expected feedback such as sound or gauge reading changes would improve the experience. The radiation dose model created during Task 4 of this effort could be improved to include static and transient radiation sources, taking input from a variety of programs such as MCNP, Microshield, and other dose-calculation algorithms. The addition of a radiation dose model to the training mockups represents a significant improvement over training systems used today that rely on mental models and "make-believe" radiation dose sources that generate nothing more than notional feedback, at best.

Based on the results of this pilot study and the previous four tasks, the full-scale virtual reality technology can make a positive impact on the design, construction, and maintenance of future nuclear power plants; however, additional effort is required to optimize its effectiveness and applicability.

## **10 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. 000000000001000149. (2000)

US Department of Energy. Generation IV Nuclear Power Systems <http://gen-iv.ne.doe.gov/> 9 February 2005.

US Department of Energy – Idaho National Engineering and Environmental Laboratory. INEEL Initiatives – Generation IV Nuclear Energy Systems. <http://energy.inel.gov/gen-iv/> 9 February 2005.

## **11 Appendix**

### **11.1 Software Descriptions**

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

#### **11.1.1 Bentley MicroStation**

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

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

#### **11.1.2 Unigraphics NX**

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

#### **11.1.3 Open Inventor**

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

#### **11.1.4 Performer**

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

#### **11.1.5 Vega**

Vega is a modular real-time simulation environment. Developed by MultiGen-Paradigm, Vega allows the user to develop real-time visual and audio simulations. The software

contains interfaces for sensors, virtual reality tools, and other visualization applications. Vega provides a graphical user interface, Lynx, which allows viewpoints, controls, and lighting to be easily added to the virtual environment. More information about the Vega software can be located at [www.multigen.com/products/runtime/vega/index.shtml](http://www.multigen.com/products/runtime/vega/index.shtml).

#### 11.1.6 Explorer

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

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

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

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

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

## 11.2 Application Definition Files

### 11.2.1 PBMR Single Model

```
// Vega Application Definition File

path {
    pathname "PBMR";
}

object "PBMR Reactor Cavity" {
    file "PBMR.iv";
    cs 1;
    pos 0 0 0 0 0;
    scale 1;
}
```

### 11.2.2 PBMR Multiple Model

```
// Vega Application Definition File

path {
    pathname "PBMR";
}

object "Citadel Building" {
    file "023580_CITADEL_BLDG.iv";
    cs 1;
    pos 0 0 0 0 0;
    scale 1;
}

object "FHSS" {
    file "023580_FHSS.iv";
    cs 1;
    pos 0 0 0 0 0;
    scale 1;
}

object "Lid Shield" {
    file "023580_LID_SHIELD.iv";
    cs 1;
    pos 0 0 0 0 0;
    scale 1;
}

object "Maintenance Floor" {
    file "023580_MAINTENANCE_FLR.iv";
    cs 1;
    pos 0 0 0 0 0;
    scale 1;
}

object "RCCS" {
    file "023580_RCCS.iv";
```

```
        cs      1;
        pos     0 0 0  0           0           0;
        scale   1;
    }

object "RCS" {
    file   "023580_RCS_1OFF.iv";
    cs      1;
    pos     0 0 0  0           0           0;
    scale   1;
}

object "RSS" {
    file   "023580_RSS_1OFF.iv";
    cs      1;
    pos     0 0 0  0           0           0;
    scale   1;
}

object "RSS Body" {
    file   "023580_RSS_BODY.iv";
    cs      1;
    pos     0 0 0  0           0           0;
    scale   1;
}
```