ASSESSMENT OF RADIATION AWARENESS TRAINING
IN IMMERSIVE VIRTUAL ENVIRONMENTS

A Dissertation in
Nuclear Engineering

by

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The prospect of new nuclear power plant orders in the near future and the graying of the current workforce create a need to train new personnel faster and better. Immersive virtual reality (VR) may offer a solution to the training challenge. VR technology presented in a CAVE Automatic Virtual Environment (CAVE) provides a high-fidelity, one-to-one scale environment where areas of the power plant can be recreated and virtual radiation environments can be simulated, making it possible to safely expose workers to virtual radiation in the context of the actual work environment.

The use of virtual reality for training is supported by many educational theories; constructivism and discovery learning, in particular. Educational theory describes the importance of matching the training to the task. Plant access training and radiation worker training, common forms of training in the nuclear industry, rely on computer-based training methods in most cases, which effectively transfer declarative knowledge, but are poor at transferring skills. If an activity were to be added, the training would provide personnel with the opportunity to develop skills and apply their knowledge so they could be more effective when working in the radiation environment.

An experiment was developed to test immersive virtual reality’s suitability for training radiation awareness. Using a mixed methodology of quantitative and qualitative measures, the subjects’ performances before and after training were assessed. First, subjects completed a pre-test to measure their knowledge prior to completing any training. Next they completed unsupervised computer-based training, which consisted of a PowerPoint presentation and a PDF document. After completing a brief orientation activity in the virtual environment, one group of participants received supplemental radiation awareness training in a simulated radiation environment presented in the CAVE, while a second group, the control group, moved directly to the assessment phase of the experiment. The CAVE supplied an activity-based training environment where learners were able to use a virtual survey meter to explore the properties of radiation sources and the effects of time and distance on radiation exposure. Once the training stage had ended, the subjects completed an assessment activity where they were asked to complete four tasks in a simulated radiation environment in the CAVE, which was designed to provide a more authentic assessment than simply testing understanding using a quiz. After the practicum, the subjects completed a post-test. Survey information was also collected to assist the researcher with interpretation of the collected data.

Response to the training was measured by completion time, radiation exposure received, successful completion of the four tasks in the practicum, and scores on the post-test. These results were combined to create a radiation awareness score. In addition, observational data was collected as the subjects completed the tasks. The radiation awareness scores of the control group and the group that received supplemental training in the virtual environment were compared. T-tests showed that the effect of the supplemental training was not significant; however, calculation of the effect size showed a small-to-medium effect of the training. The CAVE group received significantly less radiation exposure during the assessment activity, and they completed the activities on an average of one minute faster. These results indicate that the training was effective,
primarily for instilling radiation sensitivity. Observational data collected during the assessment supports this conclusion.

The training environment provided by the immersive virtual reality recreated a radiation environment where learners could apply knowledge they had been taught by computer-based training. Activity-based training has been shown to be a more effective way to transfer skills because of the similarity between the training environment and the application environment. Virtual reality enables the training environment to look and feel like the application environment. Because of this, radiation awareness training in an immersive virtual environment should be considered by the nuclear industry, which is supported by the results of this experiment.
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Chapter 1

Introduction

Experts expect the nuclear industry to undergo a renaissance in the coming years with the construction of new reactors in the U.S. and abroad. The specter of global warming and its association with greenhouse gases, standardized power plant designs, and a simpler licensing process have contributed to a change in attitudes relating to nuclear power and the expected resurgence and growth of the industry. At the same time, the trained workforce in the industry is aging, since few people entered the workforce during the lean times in the 1980s and 90s. This aging workforce is nearing the point of retirement in many cases, and there are few people to fill the many jobs, forcing many to delay retirement. The pending retirement of many in the current workforce and the potential of new plant construction for the first time in decades make the training of the future nuclear workforce a crucial matter (Michal, 2005). To meet the future needs, the industry will have to train more people, faster and better if they expect to maintain the personnel levels at the 103 existing plants, not to mention meeting the needs of the proposed new plants.

Technology, in the form of immersive virtual reality, may offer a solution for rapidly and effectively training new workers to meet the industry’s needs, which is important because, according to Michal (2005), it takes three to five years to train personnel in nuclear power plant maintenance and engineering. Virtual reality (VR) technology takes many forms, ranging from 3-D perspective views shown on a
conventional desktop monitor, to a multi-wall high-fidelity immersive virtual environment such as a CAVE™. Much of the previous research in the area of VR has focused on the study of the interface with the computer-generated environment, typically in lower fidelity environments. Immersive VR provides a stimulating training environment because it can present training material in the context of the actual environment where it is to be applied in the field. VR can safely simulate dangerous environs such as smoke, fire, or radiation, and it can present the simulations in full-scale so that users are able to experience the training world in the same way they experience the physical world. These features make the virtual environment a strong candidate for future training needs, a fact supported by educational psychology and theories of training.

Training and Learning

Training is defined as “those instructional experiences that are focused upon individuals acquiring very specific skills that they will normally apply almost immediately” (Smith & Ragan, 2005, p. 5). Numerous scholars have studied training and learning, forming a myriad of theories attempting to explain how people learn. Some of these theories contend that people construct their own knowledge and understanding of concepts based on the information presented to them, while others believe that learning is a subject’s response to the stimulus of an external environment. Hands-on learning is a key way of applying the former theory. Additionally, the concepts of similarity and physical and functional fidelity have been introduced to attempt to quantify the effectiveness of hands-on learning. Immersive virtual reality presented in a CAVE™
provides hands-on style activity in the context of the actual environment in the safety of a computer-generated environment.

Howard Gardner’s theory of multiple intelligences contends that learners acquire information in different ways, which is an attempt to explain why different people are more skilled in certain areas than others. Professional athletes have strong physical intelligence, a virtuoso may have strong musical intelligence, and an architect might have a strong spatial intelligence, for example. It follows that, ideally, training should reach personnel having the different intelligences, and those developing training materials should be aware that people have different strengths and skill-sets, and should design training materials accordingly. Virtual reality is capable of presenting information reaching multiple modalities to achieve a deeper understanding in the learner.

There is a movement underway to optimize human performance in the nuclear industry, and training is a primary component of this optimization. Multiple training methods exist to transfer information from an instructor to a learner. Each of these methods has applications where it is well-suited. It is generally left to the instructor to select a training method. While no prescriptive model for selecting a training method exists, there are numerous guidelines available to assist the instructor in making this choice. Common training methods in the nuclear industry include computer-based training, classroom instruction, and physical mockup training. Each of these methods is applied in varying degrees to teach the information and skills personnel working in the industry need to know. Virtual reality presents a novel method for training since it provides components that are missing from the suite of current methods, such as the
capability to teach skills in the context of the plant with the addition of accurate
simulated radiation dose.

One method of optimizing human performance currently being employed in the
nuclear industry is the use of generic mockup training, such as the Performance Simulator
at Susquehanna Steam Electric Station. Mockups, one-to-one scale hands-on training
environments, feature highly authentic training since the mockups are often constructed
from the same equipment installed in the plant. Training on mockups tends to be more
engaging for the user since it is a hands-on, active task. Because of this, mockup training
is a popular training medium, where possible.

One of the most well-known mockups used in the nuclear industry is the control
room simulator that is required at each plant. The control room simulator is designed to
train reactor operations personnel to perform error-free operations under normal and
abnormal conditions. Current control room mockups feature all hardware exactly as it
appears in the actual control room. The only difference is that the hardware response is
driven by computer models. The training discussed in this research covers the use of
physical mockups beyond the control simulator, such as those used for task training or
human performance optimization.

While highly appropriate for the types of skill training and task training that are
common in the nuclear industry, mockups are not appropriate for all tasks. Mockups are
expensive to build and maintain, but the training they provide is invaluable. It is
common for mockups to be constructed for high-value or high-risk tasks such as steam
generator replacement, vessel head replacement, or control rod drive maintenance. While
the mockups allow personnel to safely practice tasks multiple times, most do not model
the radiation environment. There are systems, such as the Teletrix, that can simulate radiation environments in the mockups, but they are not commonly used due to expense or skepticism related to the simulation technology. Since radiation exposure is a principal consideration in the planning of these kinds of tasks, one would expect radiation awareness to be trained on the mockup as well. This is generally not the case.

Immersive virtual reality environments provide many of the same training characteristics as mockups, but they can also present additional information such as radiation levels or equipment specifications. Technology has advanced to the point where it is now possible to create high-fidelity audio-visual environments where training can be performed. These environments can be generated by Computer-Aided Design (CAD) or 3-D modeling software. The next generation of nuclear power plants has been designed using 3-D CAD so virtual mockups of the entire plant can be created prior to construction of the actual plant. These models can be combined with radiation simulations such that radiation exposure can be managed by enabling workers to optimize tasks by walking through simulated activities in the virtual radiation environment. Tasks can be adjusted and methods can be changed based on the radiation exposure. Beyond task training, the technology may be useful for training abstract concepts such as radiation awareness.

Statement of Purpose

Virtual reality has been applied in numerous training contexts ranging from military aircraft flight trainers to fighting fires on ships. Few of these applications to date
have used projection based immersive virtual reality; most have focused on desktop VR and Head Mounted Displays. The research presented in this dissertation evaluates radiation awareness training using an immersive training environment, a 5-sided CAVE™ VR display. The VR training was compared to other methods such as computer-based training and hands-on training with a simulated radiation meter. Much of the previous published research in the area of VR describes the development of applications with little background as to why VR is suited for that application. This work attempts to bring together the areas of educational theory, virtual reality, and nuclear engineering to describe how existing radiation awareness training can potentially be improved by adding an activity, which can be simulated in a virtual environment. The hypothesis of this research is that radiation awareness is higher in workers that have received activity-based training in a full-scale virtual mockup than those trained using traditional methods such as computer-based training.

This research was inspired by this author’s personal experiences with education and training in the nuclear industry. Three events clearly illustrate the need for an investigation of nuclear training methods. First, in a senior-level thermal-hydraulics class, the instructor described his research involving the effect nucleation sites on boiling by using vivid examples and images to explain how boiling occurs and then how polishing a surface and reducing the number of nucleation sites can delay the onset of boiling. To this day, the vivid illustration of the phenomenon is recalled every time water is boiled on the stove. Second, the concept of criticality was explained in concept in numerous classes from a senior-level power plant design class to a graduate-level class in neutron kinetics. It wasn’t until the hands-on experience provided by a reactor operations
lab that the concept was fully understood. Third, the author received radiation worker training certification at a power plant in the Midwest during graduate school in the late 1990’s. The course involved a combination of simple computer-based training and classroom instruction, with minimal hands-on activity. When it came time to apply the knowledge from the training course in the field, it was difficult to recall the proper procedures.

While only anecdotal in nature, these three situations exemplify that conventional training doesn’t always transfer to the audience. Some people learn best by listening to lectures, while others need to experience the material in order for it to truly transfer. In some cases, this can come from computer-based training, but often it is only after hands-on immersion in a situation that theories or concepts can be internalized and applied.

The arrangement of the subsequent chapters of this dissertation is listed below. Chapter two discusses basic information about training, which includes the definition of training, a variety of theories in educational psychology and their application to training, and the current means of training personnel typical in the nuclear industry. The third chapter introduces the concept of virtual reality (VR) and relates some of the features of VR that make it a potential training tool. Training in the nuclear power industry including regulations and organizations governing training, the methods for creating training programs, the use of mockup training, and four case studies are discussed in chapter four. Chapter five combines the concepts discussed in the three preceding chapters in a discussion of the previous work using VR for training and familiarizing personnel with nuclear power concepts and operations. Chapter six introduces the methodology used to assess the immersive virtual environment as a radiation awareness
training tool. Development and execution of a pilot experiment designed to assess how well information is transferred from the training environment to actual plant environment using three different methods is covered. The pilot experiment compared computer-based training similar to that delivered in utility training programs today, computer based training supplemented with a hands-on activity with a simulated physical radiation survey meter, and computer-based training supplemented with training activities in a virtual environment. Chapter seven presents changes to the pilot experiment and the procedure and results for a second set of experiment trials. Chapter eight summarizes the work performed in this dissertation, offers conclusions based on the results of the experiment, and suggests future directions for research in this area.
Chapter 2
Education and Training Theories

Training is one way of transferring information from personnel that possess the knowledge or skill to those that need it. Numerous researchers have defined training. Smith and Ragan (2005) define training as “those instructional experiences that are focused upon individuals acquiring very specific skills that they will normally apply almost immediately” (p. 5). The British Department of Employment (1978) defines it as “a planned and systematic effort to modify or develop knowledge/skill/attitude through learning experience, to achieve effective performance in an activity or range of activities. Its purpose, in the work situation, is to enable an individual to acquire abilities in order that he or she can adequately perform a given task or job (Buckley & Caple, 1990). Smith & Ragan (2005) continue, “Much instruction in business, military, and government settings can be termed training because the experiences are directed toward preparing learners with specific on-the-job skills” (p. 5).

In the nuclear industry, much of the instruction that occurs can be classified as training. Training and education are related, but a distinction between them can be made. According to Tobias and Frase (2000), the differences between education and training can be summarized by looking at the specificity of objectives and the training time. Education tends to have broader goals than training; training tends to focus on specific tasks, whereas education is meant to provide a broader understanding. Education tends to be a long-term process concerned with general understanding of phenomena, while
training is usually a shorter-term activity that focuses on performance of a specific task. Edmonds (1985) also notes that a primary difference between education and training is the fact that instructors training the personnel are preparing them to perform specific duties, whereas in education, students are prepared with general knowledge and skills. Buckley and Caple (1990) summarize the above thoughts by saying “the changes brought about by training are often more immediately observable in the short term whereas education and development are more likely to show their influence in the longer term and, possibly, in a more profound way” (p. 15).

Learning is defined as “a relatively enduring change in observable behavior that occurs as a result of experience” (Eggen & Kauchak, 2001, p. 214). In the words of Bruner (1977), “Learning should not only take us somewhere; it should allow us later to go further more easily” (p. 17), leading to a better understanding of the world.

A number of theories describing how people construct knowledge and understanding have been proposed in the educational psychology community. One theory, constructivism, claims, according to Mantovani (2001), “we construct our own reality through interpretation of personal perceptual experiences...” (p. 210). He continues, “constructivism holds that students learn best when they build their own understanding of content by directly interacting with it, rather than receiving pre-structured content from an external source, such as a teacher or text” (p. 210). Eggen and Kauchak (2001) summarize the characteristics of constructivism: “learners construct their own understanding; new learning depends on current understanding; learning is facilitated by social interaction; and meaningful learning occurs within authentic learning tasks” (p. 294).
The theory essentially holds that learners assimilate information through experience. Given the information and environment surrounding them, they develop a unique understanding of the world around them, which is particular to them. Also, this constructed understanding depends on previous knowledge and understanding of related information, so it is important to develop a substantial base of information to build further understanding. For these reasons, experience is crucial to understanding. Famed educational theorists Jerome Bruner and John Dewey proposed theories that relate to the development of new understanding based on what is experienced.

Dewey was a proponent of progressive education where learning was fostered through experience (Dewey, 1938). He states,

The effect of an experience is not born on its face. It sets a problem to the educator. It is his business to arrange for the kind of experiences which, while they do not repel the student, but rather engage his activities are, nevertheless, more than immediately enjoyable since they promote having desirable future experiences (p. 27).

He places the onus of creating a positive learning environment on the instructor, believing that creating this environment where learning is interesting and enjoyable will lead to better learning. One way of doing this is by enabling students to learn via experience, since it is enjoyable and meaningful to them.

Bruner (1977) proposed the idea of discovery learning, which holds that the best way to learn new material is to discover how what you already know can be extended to cover what you do not yet know. While it would be inefficient to learn everything from the ground up, discovery learning is useful for situations where learning the relationships between concepts is important. Towne summarizes this argument.
It is crucial to understand what instructional roles discovery worlds serve well and what they do not. As a means for supporting practice, for allowing learners to discover shortcomings in their knowledge, and for answering specific questions about the effects of particular actions discovery worlds have proven to be exceptionally effective. These approaches can also be effective in refresher training for skilled personnel, particularly when the user wishes to brush-up on previously learned skills prior to some specific job requirements such as a field repair or retrofitting task (Towne, 1995, p. 11).

According to Biehler & Snowman (1990), two conditions must be present for discovery learning to work well. First, the learners must have a well-organized body of relevant knowledge. Second, the learner must feel “sufficiently confident about their learning skills to engage in independent forms of problem solving” (p. 428). In the nuclear industry, these two factors should be present once a person successfully completes the nuclear general employee training (NGET) and radiation worker training (RWT), since these required courses are designed to teach workers the information and concepts necessary to safely work in a radiation environment. This training provides a general knowledge base upon which hands-on training can be applied to extend their knowledge.

Learning theories apply to both education and training situations. Many researchers have studied the learning process, forming theories to explain people’s ability to learn. When discussing learning, one must first consider what is being learned. Bloom (1956) categorized this material into three domains: cognitive dealing with knowledge, psychomotor dealing with skills, and affective dealing with attitudes. The use of these categories is commonplace in the educational literature. When writing learning objectives, the knowledge, skills, and attitudes to be taught are often listed. In the years since the three categories were proposed, the domains have been refined by adding different levels of mastery to each.
Bloom suggests that cognitive learning consists of six levels: knowledge, comprehension, application, analysis, synthesis, and evaluation (1956). Specific learning behaviors for each level can be defined to assist the instructor in writing educational objectives. Seels and Glasgow (1998, p. 61) provide an interpretation of the six levels:

1. Knowledge represents the ability to remember an idea, material, or phenomenon in a form similar to that in which it was originally encountered with no further interpretation or understanding.
2. At the comprehension level, the learner has the ability to understand the literal message contained in the lesson.
3. A learner at the application level has achieved the ability to apply knowledge without prompting or being shown how to use it.
4. At the analysis level, the learner can decompose information or ideas into their constituent parts and detect relationships between the parts and how they are arranged.
5. A learner capable of synthesis has ability to assemble elements or part skills to form a new whole.
6. At the evaluation level, the learner is able to make qualitative or quantitative judgments concerning the value of learned ideas, works, solutions, methods, materials, etc.

The affective domain, described by Krathwohl, Bloom & Masia (1964), deals with attitudes of learners, which is demonstrated as interest, awareness, responsibility, and the ability to interact with other. It generally relates to emotions, attitudes, appreciations, and values. Seels and Glasgow (1998) discuss the five levels of the affective domain: receiving, responding, valuing, organization, and characterization by value and value set. These levels are can be further defined:

1. Receiving is simply being aware of or sensitive to the existence of certain ideas, material, or phenomena and tolerating them
2. Responding demonstrates a minimal level of commitment to the idea, material, or phenomenon by responding to it.
3. Valuing is being willing to be perceived by others as believing the ideas, materials, or phenomena.
4. Organization requires the learner to assimilate the value with those values that are already held, thereby creating a harmonious and internally consistent philosophy.
5. Characterization by value or value set is acting consistently based on the values in which the learner believes.

A taxonomy of the psychomotor domain was developed by Harrow (1972). Harrow proposed six levels of psychomotor skills: reflex, fundamental movements, perceptual abilities, physical abilities, skilled movements, skilled movements, and non-discursive communication. Again, Seels and Glasgow (1998) summarize the six levels:

1. Reflex describes actions that occur in response to some stimuli that are inherent in the learner.
2. Fundamental movements describe those that are formed by combining reflex movements. These form the basis for complex, skilled movements.
3. At the perceptual level learners are able to interpret various stimuli that enable them to adjust to their environment. The stimuli can be visual, auditory, kinesthetic, or tactile. The perceptual level also includes elements of cognitive behavior.
4. Physical activities demonstrate movements performed with endurance, strength, vigor, and agility, which shows that a certain level of proficiency has been achieved.
5. Skilled movements demonstrate that a certain degree of efficiency has been achieved in the performance of a complex task.
6. Nondiscursive communication is achieved when communication can be made through movements of the body, which may range from expressions to choreographics.

Since mastery in each of the domains is often not necessary for the completion of a task, the instructor must consider what depth of understanding is necessary. For example, time constraints may require “just-in-time” training, training specifically designed to teach a specific emergent activity, to be performed. Just-in-time training typically does not allow sufficient time or practice to achieve mastery. In this case, the instructor must decide how well the task must be performed.

Training may be designed to achieve differing levels of knowledge, ranging from novice to expert. Acquisition, application, and generalization classify different levels of
understanding (Towne, 1995). The acquisition stage is where new concepts are first studied by the learners. When learners reach the application stage, they are able to apply the knowledge or concept to situations that are very similar to the original training situation. Finally, when learners reach the generalization stage, they can apply knowledge to situations that are significantly different than the original situation. The National Research Council (1999, p. 19) lists differences between novices and experts:

- Experts notice features and meaningful patterns of information that are not noticed by novices
- Experts have acquired a great deal of content knowledge that is organized in ways that reflect a deep understanding of their subject matter
- Experts’ knowledge cannot be reduced to sets of isolated facts or propositions but, instead, reflects contexts of applicability: that is, the knowledge is “conditionalized” on a set of circumstances
- Experts are able to flexibly retrieve important aspects of their knowledge with little attentional effort
- Though experts know their disciplines thoroughly, this does not guarantee that they are able to teach others
- Experts have varying levels of flexibility in their approach to new situations

It takes significant time and dedication to become an expert, but it is not always the goal of the learner to become one. Sometimes learners will do just enough to satisfy the current need or requirement. The instructor must be aware of this fact. If error free
performance or mastery is the goal, that objective must be communicated to the learner, and the assessment must reflect that. Smith and Ragan (2005) state,

The ability to verbally state the relationship between concepts may be helpful in learning to apply a rule; however, stating the principle is not sufficient evidence that the rule has been learned. A principle must be applied to show that it has been learned. The failure to recognize this distinction is very common in both training and educational settings (p. 205).

This shows a difference between declarative knowledge, knowing that something is true and true understanding and subsequent application of a concept. Because it is difficult to judge true understanding of a concept, examinations often concentrate on the superficial understanding of concepts. In radiation awareness, for example, the concepts of time, distance, and shielding, three strategies to reduce radiation dose, should be well known to those who have completed a radiation worker training course. However, when asked to put these concepts into practice, workers often encounter problems. There is clearly a disconnect between the superficial knowledge of the concept and the application of the concept in the field.

In addition to Bloom’s work, Gagne has also created a taxonomy of learning tasks. Gagne (1985) suggests that learning can be categorized into verbal information, intellectual skills, psychomotor skills, cognitive strategies, and attitudes. Verbal information, also referred to as declarative knowledge, is defined as simply knowing that something is true. Intellectual skill refers to knowing how to perform a task. Psychomotor skills are learned movements that can be assembled to perform a physical task. The cognitive strategies category refers to a person’s self-knowledge of how he or she learns a task. Finally, attitudes are mental states that influence a person’s choices or
actions. These five areas are quite similar to those proposed by Bloom, but they are somewhat more specific.

Examples of the application of knowledge, skills, and attitudes can be found in the nuclear industry. Safety culture and the desire to do a “good job” are examples of attitudes that the nuclear industry would focus on in training. Replacing a valve’s packing and performing a valve alignment are examples of skills that would be trained. Visually distinguishing between various types of valves or determining the location of a piece of equipment is an example of knowledge that might be trained. Tasks can also demonstrate components of more than one domain. For example, diagnosing a problem, finding the correct procedure, and correcting the problem can be represented by both the cognitive domain (diagnosis and procedure selection) and the psychomotor domain (taking corrective action).

Unfortunately, passing information between the instructor and the learner is not as simple as the instructor telling the learner what he or she needs to know. People learn differently. In an ideal world, trainers would be able to design training that is directed towards each individual’s learning style; however, this is not practical. People have a preference towards learning styles, such as trial and error, perceptual organization, behavior modeling, mediation, and reflection (Buckley & Caple, 1990). Trial and error learners search for the “right” answer to a problem by testing different methods and determining whether or not they have achieved success after each attempt. Learners using perceptual organization use all available stimuli and attempt to develop a pattern to direct or control their behavior. Behavior modeling involves observation of a task being performed and then imitation of that performance. Skills acquired from oral or written
communication are referred to as mediation. Finally, reflection, a method similar to trial and error and perceptual organization, involves exploration and discovery of potential solutions and determining why things happen the way they do. People may prefer to learn by any of these different methods, though unfortunately the instructor typically makes the determination of which of the methods will be utilized by the training program due to time or monetary resource constraints.

Other research suggests that besides preferring different learning styles, learners also demonstrate different forms of intelligence. The theory of multiple intelligences proposed by Gardner (1983) suggests that there are seven distinct forms of intelligence that each individual possesses in varying degrees. These forms of intelligence are: linguistic, musical, logical-mathematical, spatial, body-kinesthetic, intrapersonal (e.g., insight), and interpersonal (e.g., social skills). Gardner believes that learning/teaching is best when it addresses the particular intelligences of each person. One point of the theory notes that the intelligences represent different content, as well as different learning methods. Gardner proposes that the assessment of learning should test multiple forms of intelligence, rather than simply focusing on linguistic and logical-mathematical. For example, using Gardner’s logic, radiation awareness should be assessed not only using a conventional examination, but also a hands-on activity to reach those who are spatial learners.

The types of activities typically required for nuclear power plant maintenance are comprised of motor skills, which control movements, and cognitive skills or subject knowledge. Gagne (1985) discusses the training of skills as depending on the task to be learned, the nature and length of the procedure to be followed, and the type and number
of part skills that comprise the total skill. The task to be learned may be simple or complex; it may be a single activity or have multiple steps; or it may be completely new or composed from previously learned sub-skills. The complexity of the procedure, how well it has been written, and the learner’s familiarity with the general subject matter can affect learning of a task. Part skills or sub-skills may make up the skill being learned, which may have been learned previously or they may be new, as well. The familiarity of the learner with background material or sub-skills can affect learning of the actual task. All of these factors can contribute to or inhibit learning of a task.

Training Methods

Common training methods used in the nuclear industry include classroom instruction, computer-based training (CBT), hands-on training, and on-the-job training (OJT). According to Towne (1995), “There is no single technology or instructional approach that will resolve all problems and meet all instructional needs” (p. 3). Fortunately, multiple methods can be used to reach learners with different strengths and to instruct different topics.

Classroom instruction in the nuclear industry typically takes the form of lecture, although it can sometimes involve demonstrations. Advantages of classroom instruction, according to Buckley and Caple (1990), are that it can easily cater to large numbers of trainees, the trainer has complete control over content and sequence, and more material can be presented in the allotted time than most other methods. Disadvantages include that it cannot effectively teach skills, the limited interaction between trainer and trainee,
the difficulty of holding the trainee’s attention due to the lack of interaction, and the requirement of a skilled presenter (Buckley & Caple, 1990). Demonstrations involve “illustration by a live performance of a task, skill, or procedure accompanied by the trainer or an assistant” (Buckley & Caple, 1990, p. 163). According to the authors, advantages include that it is easy to attract trainees’ attention, it reinforces correct work methods, it shows relationships between tasks, and the speed can be adapted based on the group. Disadvantages include the amount of preparation required by the trainer, the time consuming nature of preparation, and the fact that it may require multiple viewings to transfer the knowledge (Buckley & Caple, 1990).

Computer based training is another method that is commonly used for training in the nuclear industry. Towne (1995) states,

Computer based training (CBT) should be a term that embraces all approaches to delivering training via computer technology. The term, however, usually refers to the most common instructional approach that has been used in the past: essentially frame-based instruction involving the computer managed presentation of facts followed by questions to the learner and then remediation conditional upon the learner’s responses (p. 3).

Computer based training can range from simple PowerPoint presentations to rich multimedia presentations using proprietary software. Widen and Klemm (1986) discuss some of the advantages of computer based training. They describe CBT by saying, “it represents interactive, self-paced training that can be conducted at any time convenient to the trainee’s schedule. In addition, student progress and attainment of objective can be recorded and documented” (Widen & Klemm, 1986, p. 642). The authors also describe properly developed CBT programs as being “fun” (p. 642). Further, they note that due to its self-paced and branching nature, CBT is ideal for requalification. Other advantages of
CBT are that it provides “color, sound, motion, videodisc capability, and the ability to mockup complex process flows and conditions” (Painter, 1988, p. 52). Buckley and Caple (1990) list the disadvantages of Computer Based Training. These include high initial development costs; the demands of administering training to large numbers of personnel; potential of fear of technology by trainee; and, most importantly, its unsuitability for skills training.

On-the-job training is commonly used in the nuclear industry. In this situation, learners are placed with mentors, experienced workers, who model for and supervise the learner as they perform tasks. Furgang (1986) describes the potential risks associated with on-the-job training (OJT):

The instructor passes along his own poor work habits to a trainee; the instructor lacks adequate technical knowledge to fully explain the material; the trainee is placed in a passive role and is not allowed to do much more that observe; the instructor omits important topics or dwells on minor ones; and the outcome of the learning is not always measured objectively (p. 59).

Simulations provide another means of training personnel. Towne (1995) defines the use of simulators for training,

A simulator is some combination of hardware and, possibly, software that provides some of the functionality of the real system. Simulators are usually used to teach people to operate complex systems. A simulator is often a slightly modified version of a complete working system, such as an aircraft. Typically the simulator is fashioned from an operational system, minus a few crucial parts… (p. xxv).

Hands-on training via simulation is further discussed by Buckley and Caple (1990). The authors state, “Simulation exercises are based on the application of skills to machinery and equipment. They are best used when access to the real equipment is difficult and when the consequences of error could be costly or a danger to life, e.g. flight simulators,
driving simulator, etc.” (p. 165). Mockup training and control room simulators can be classified as simulation training. According to Buckley and Caple (1990), the advantages of simulation training are (p. 165):

- Introduces an element of realism
- Involves a high level of activity which arouses interest and motivates trainee
- Can draw upon the experience of trainees
- Can be used as a measure of level of competence of trainees
- Involves high level of activity
- Can include activities involving critical decision making without danger

The disadvantages of simulation training according to Buckley and Caple (1990, p. 165) are:

- Preparation and conduct of exercises is time consuming
- Can be very expensive depending on what resources are required and the level of fidelity which is needed
- High level of skill required by trainer to direct, manage, and control the exercises

Simulations are often used in situations where the actual environment is too dangerous to expose personnel. Barczy (1989), for example, discusses the use of a simulation via hands-on training for Hazmat response teams at the Center for Hazardous Materials Research at the University of Pittsburgh by stating, “Field simulations are an essential part of CHMR’s on-going 40-hour health and safety training program, a reflection of CHMR’s belief that hands-on training leads to proper hazardous materials handling” (p. 90). The hazmat training course involves a combination of classroom learning supplemented with hands-on field exercises. Barczy believes the hands-on training is a necessary part of learning to work in a hazardous environment. Training using simulation is often applied in the nuclear industry, as well. These applications are covered in chapter four.
Selecting a Training Method

Selection of the proper training method from those described in the previous section is one of the most important decisions an instructor makes. Selecting the right training method for the job will ensure higher transfer to the learner; selection of the wrong method can leave the learner lost. There is no perfect training method, and, as the previous section showed, each method has strengths and weaknesses. The instructor must balance these strengths and weaknesses while considering the task being trained and the learning styles of the personnel being trained. The National Research Council (1999) states,

Books and lectures can be wonderfully efficient modes of transmitting new information for learning, exciting the imagination and honing students’ critical faculties – but one would choose other kinds of activities to elicit from students their preconceptions and level of understanding, or to help them see the power of using meta-cognitive strategies to monitor their learning. Hands-on experiments can be a powerful way to ground emergent knowledge, but they do not alone evoke the underlying conceptual understandings to aid generalization. There is no universal best teaching practice (p. 18).

That said, a number of researchers have attempted to develop processes to aid trainers with the selection of proper training methods for different tasks, but none of these processes directly address mockup training similar to that performed by nuclear power plants. While this is true, it is possible to make a few generalizations that may enable one to determine when a mockup should be used for training. Buckley and Caple (1990) state that learning principles, target population, and constraints influence the selection of training, while Segrue and Clark (2000) advocate selecting media based on the relative
ability of the trainee and the overall purpose of the training. Gagne (1985) suggests that trainees’ experience levels and reading levels influence the selection of training material.

Research suggests that the training situation should be made as similar as possible to the actual activity. Segrue and Clark (2000, p. 216) state, “The only reason one medium might be more suitable than another for a particular training task is that the task requires the presentation of some information or practice activity that calls for particular media attributes… The only way to justify selection of one particular medium or media mix over another (beyond relative costs and practicalities of implementation) is the media’s ability to support the kind of cognitive activities deemed necessary to attain the targeted task performance.” In the same vein, Buckley and Caple (1990, p. 146) note, “If the stimulus conditions and response requirements in the environments of training and work are very similar, then there should be high positive transfer. Some forms of on-the-job training come close to fulfilling this kind of specification and this is the reason no doubt, why this form of training can prove to be very effective.” When on-the-job training cannot be performed, mockup training is designed to mimic the actual work situation, providing a similar benefit.

Furthermore, Baldwin and Ford (1988) propose two aspects of the notion of similarity. The first is physical fidelity, which is the extent to which the training conditions (task, equipment, and surroundings) are similar to the work environment. The second is psychological fidelity, which is the degree to which the trainee attaches similar meanings to what is introduced in the training environment and what exists in the work context. When selecting a training method, the instructor or developer should account for each of these notions, making the training situation as similar as possible to the actual
work environment. Buckley and Caple (1990) add that where it is feasible to do so, the trainer should make the training situation similar to the work situation in terms of stimulation conditions and response requirements. This is one of the key features of mockup training, which explains why it is so widely used. The mockup is typically as close to the actual environment as is possible without being there.

In a list of limiting factors for instructional situations, Gagne (1985) highlights tasks requiring error-free performance and learner characteristics, two factors that also apply to the design of training for nuclear power plants. Error-free performance is the goal of all training programs in the nuclear industry, because there are significant costs associated with failure. The learner characteristics Gagne identifies are age/educational experience and reading level. He notes that much has yet to be learned concerning the proper ‘matching’ of learner characteristics and media properties. Mockups or similar media provide valuable hands-on training, which Gagne believes is the most effective form of training. This is evident when he states,

> When fault-free performance is required as an outcome of instruction, the medium employed must be either the real equipment used in the job or profession or a highly faithful simulation of the task or tasks to be performed with the use of this real equipment... In general, it may be said that the requirement of fault-free performance limits media choice to these two possibilities: real equipment or real task simulation (p. 284).

Gagne (1985) proposes that in the selection of training methods, the approach can be simplified by dividing the five categories of learning outcomes into two sets. The first set is comprised of intellectual skills, cognitive strategies, and motor skills, and the second set contains verbal information and attitudes. The components of the first set generally require some kind of feedback for the user to stimulate learning so they are
typically best trained using interactive media. In the second set, attitudes are best developed by observing examples designed to influence a “personal action toward some object, person or event,” and verbal information, better known as declarative knowledge, can be learned by listening, reading, or looking at pictures. As was stated before, skills and tasks commonly performed in the nuclear industry most often fall into the first set, while some of the more complex concepts such as safety culture and human performance improvement fall into the second.

Multimedia training is a way to use multiple training methods to cover a single task. This enables trainers to design activities that cover more than one of the categories listed above. This type of training may be effective for a wider audience since it can account for different learning types. An example of multimedia training would be classroom training followed by hands-on activity or classroom training which includes a demonstration.

Training Assessment

Once a training method has been selected, the instructor or training staff must decide upon a way of assessing whether or not the training is successful. Smith and Ragan (2005) list formats for assessment; two of which are commonly used in nuclear power plant (NPP) personnel training. These formats are observation of on-the-job performance and simulations. Performance assessments include tests of higher-order knowledge and skills in the real-world context in which they are actually used. Some
examples of assessments would be direct observation, solving open-ended problems, and simulations.

According to Smith and Ragan (2005), observation of on-the-job performance is one of the better ways to assess learners’ performances because they are being observed in real-world situations. It tends to have a high degree of validity and reliability because the learner is being asked to put their training to work in an actual activity, so this is a true measure of whether or not they are capable of performing a specific task. Rating scales or check lists can be used to assist the instructor in evaluating the learner’s progress in these cases. On-the-job training is used in the nuclear industry, pairing experienced personnel with inexperienced personnel during the performance of routine activities.

Simulations provide the instructor with another means of assessment, according to Smith and Ragan (2005). Because cost, danger, and other factors can make it impossible to perform direct observation of an activity in the field, simulations are often used in these cases. The conditions presented in a simulation can be controlled and repeated. In addition, the student can be observed while performing the work activity, and rating scales and checklists can be used to assess the student’s performance. Simulations provide an authentic context in which theory learned in one environment can be put into practice in an environment similar to the one where it will be required.

In addition to observation and simulation, other means of assessment are available including tests and examinations, recall items, recognition items, and constructed answer items. Recall items are used to judge declarative knowledge, general knowledge of a concept in verbatim, paraphrased, or summarized form. Recognition items require the
student to select the correct answer from a group of possible answers. Depending on the wording of the question, recognition items can require more or less understanding of the information being tested. Finally, constructed answer items often require a student to display more in-depth knowledge of information, where memorized information is often insufficient. When actual performance cannot be measured, tests and examinations have to suffice. At the end of the computer based training applications that are commonly used in the nuclear industry, a worker’s knowledge is typically assessed using traditional testing methods, exams, rather than hands-on activities.

Seels and Glasgow (1998) discuss the use of cognitive tests and various types of performance tests as means of assessment. Cognitive tests, according to the authors, are best for testing the acquisition of general knowledge of facts. Performance tests measure a trainee’s ability to do something. Performance can be measured against a predetermined standard or evaluated as steps in a process. The authors note that performance tests directly measure ability and are, therefore, “more valid than written tests” (p. 88). At the same time, performance tests require more subjective analysis by the reviewer which can make evaluation less valid since evaluator bias can be a factor. A combination of the two types of tests would provide a more complete assessment of performance that should yield a better appraisal of not only what subjects know, but also whether or not they can apply their knowledge and skills.

The authors define five categories of performance assessments: process, products, portfolios, projects, and performance (Seels and Glasgow, 1998). Of these, process and performance can be applied to nuclear power training activities. Process objectives are those that involve learning or following a series of steps to reach a final
goal, such as following a procedure, solving a problem, or diagnosing a fault. These tasks are generally scored by developing a series of criteria that apply to the performance of a task. Performance objectives can be rated by observing the completion of a task. Again, the reviewer must define specific task-related criteria so that the exercise can be scored.

Reinforcing this point is the concept of authenticity. Seels and Glasgow (1998) define authentic assessment as examining the performance of a trainee directly on “real” tasks rather than pencil and paper tests where learning must be inferred. Reliability and validity, two key components of assessment, are achieved by developing specific criteria for scoring. The authors note that testing using authentic assessment better simulates the complexities of the “real world” situations that trainees will experience in the field. Again, mockup training and simulations are designed around this concept.

The success or failure of training is typically assessed by evaluating how well the information delivered by the instructor was passed on to the student, a concept known as transfer of training. In a National Research Council (1999) report, the authors discuss factors that influence the transfer of training. These include context and relationships between learning and transfer conditions. Context is important because it enables learners to see the information in terms that are familiar to them. Once a base has been established, variants of the context can be given to expand the learner’s knowledge. The relationship between learning and transfer conditions is important because, “Many theorists argue that the amount of transfer will be a function of the overlap between the original domain of learning and the novel one” (National Research Council, 1999, p. 51).
This would suggest that the optimum training environment would be exactly the same as the environment where the knowledge or skill is to be applied.

Summary

This chapter discussed general theories concerning learning that can be applied to training, selection of training methods, and assessment of training. The theory of constructivism holds that learners build their own understanding of concepts based on material provided to them. In order for constructivism to work, learners must be provided with sufficient learning materials and accurately constructed environments. Much work has been done in the area of characterizing learning, which includes the discussions of multiple learning styles, multiple levels of learning, and multiple forms of intelligence. Together, all of these variables can complicate the selection of training methods, since instructors must be cognizant of the factors when trying to develop curricula to maximize learning and at the same time doing so with limited resources. In task and concept training, the concepts of physical and psychological fidelity must be addressed to ensure transfer of learning. Transfer is measured by various means of assessment, which can take the form of cognitive tests and performance tests, among others. By understanding the underpinnings of how people learn, a trainer can select the proper training method for the specific task to ensure that the concept being trained is transferred to the learner. The next chapter discusses one technology, immersive virtual reality, which could potentially be used for training complex concepts, such as radiation awareness.
Chapter 3

Virtual Reality and Virtual Mockups

Based on the information presented in the previous chapter regarding the ways in which people learn and the importance of similarity between the training environment and the actual environment, virtual reality and full-scale virtual mockups may provide a way of reaching larger training audiences with engaging, dynamic, and multi-sensory content. This chapter supplies an introduction to virtual reality technology, makes the case for why virtual reality should be considered as a training tool, and provides some examples of virtual reality training applications used in other industries.

Flexibility, repeatability, spatial fidelity, authenticity, safety, and the ability to provide context are some of the key features of virtual reality simulations that make it a potential training method for radiation awareness training. The nuclear power plant could be characterized as a hazardous environment, and safely working in the radiation environment requires significant training. Research shows that repetition and context are important features that improve learning, and these can be provided by virtual environments.

Grigore Burdea, a renowned researcher in the virtual reality field, defines virtual reality (VR) as “a high-end user-computer interface that involves real-time simulation and interactions through multiple sensorial channels. These sensorial modalities are visual, auditory, tactile, smell, and taste” (Burdea, 2003, p. 3). Virtual reality, however, is most often associated as being high-fidelity, interactive visual environments. These
environments can also feature positional audio and force feedback control devices, though they tend to be dominated by the visual sense.

Burdea proceeds to describe three “I’s” of virtual reality – interactive, immersive, and imagination. Virtual reality simulations are interactive, meaning the user can alter parts of the simulation. The simulations are immersive such that users are drawn in to the virtual world, enabling them to suspend belief for the period that they are experiencing the simulation. A believable environment for the user can be created using high-fidelity simulations that feature realistic visual imagery and positional audio. Finally, the user may use imagination to create worlds that are fantastic or realistic, since virtual reality technology enables both to be created (Burdea, 2003).

A number of components are assembled to create a virtual reality system, shown in Figure 1. Specialized hardware used to display the virtual reality simulation typically includes a high-end computer with dedicated video rendering capabilities. The data, rendered as small triangles called polygons, is output to a display. The display can be a monitor in either monoscopic (2-D or 2.5-D perspective) or stereoscopic projection (3-D), a head mounted display, or an immersive virtual reality display. Rendering software interfaces with the computer hardware to draw and redraw the dynamic images many times per second, a quantity called frame rate, for the simulation. The user interface enables the user to navigate and interact with the simulation. However, without content, the hardware would have nothing to display. Content may include such material as CAD models, computational fluid dynamics (CFD) simulations, architectural models, sensor data, or molecular interactions, depending on the chosen application. The components of a VR system will be described in further detail in the sections that follow.
Virtual reality simulations are often categorized into two groups, desktop virtual reality and immersive virtual reality, based upon how they are displayed. Desktop virtual reality, sometimes referred to as 2.5-D, is presented from a first-person perspective on a desktop monitor (Hanes & Naser, 2004). These simulations can range from a first-person walkthrough, to three-dimensional CAD, to entertainment applications such as video games. The interactions in a simulation can range from environments where users may only view objects, to an environment where the user can move objects or interact with controls. Objects are drawn in a perspective view to provide a sense of depth. Using a monitor and software capable of generating stereoscopic images, some desktop systems may even offer a fully 3-dimensional view, a capability that is becoming more common as computing power increases. A depiction of desktop virtual reality (2.5-D) is shown in Figure 2.
Immersive virtual reality generally consists of Head Mounted Displays (HMD) and Immersive Projection Displays (IPD). Immersive virtual reality is characterized by a large field of view that appears to surround the user, which provides the user with a more seamless view of a virtual environment, but they are more expensive than desktop virtual reality systems. Head mounted displays have small screens mounted in front of the eyes in a helmet-like device worn on the head. They provide a lower cost solution for presenting the immersive form of virtual reality, although these can be uncomfortable to wear for long periods of time, offer a smaller field of view, and can contribute to motion sickness-like symptoms since the user is entirely isolated from the external environment. However, newer HMDs have addressed some of these criticisms by providing larger, brighter displays.

Figure 2: Desktop Virtual Reality
Immersive projection displays typically feature computer generated images on the back of large screens, a method known as rear-projection. A number of different formats exist, but the most well-known is the CAVE Automatic Virtual Environment (CAVE™), which debuted in 1992 (Cruz-Neira, 1992). Preddy and Nance (2002) describe the CAVE™ as being, “composed of three to six projection screens driven by a set of coordinated image-generation systems. It is assisted by a head and hand tracking system that produce a stereo perspective and isolate the position and orientation of a spatial 3-D input device” (p. 127). IPDs provide the highest fidelity projection of a virtual environment, but they are very expensive to install and maintain. The HMD and the IPD technologies are shown in Figure 3.

Figure 3: Immersive Virtual Reality Technology: IPD (L) and HMD (R)

The CAVE™ environment provides the largest, most immersive field of view of currently available VR technologies. Large displays, similar to the CAVE™, have been shown to be beneficial for learning activities, resulting in increased task performance. Research by Tyndiuk, Lespinet-Najib, Thomas, and Schlick (2004) evaluated
performance of subjects completing manipulation tasks, prime travel tasks, and naïve
task environments. Performance of low-attention subjects improved as did the general performance of subjects on the manipulation and
naïve travel tasks. Subjects who had been identified as having low levels of attentional abilities performed particularly well in the large screen environment. Along the same lines, Deisinger, Cruz-Neira, Riedel, and Symanzik (1997) compared sense of presence, a measure of a subject’s feeling of “being there,” and immersion in stereoscopic presentations on Monitors, HMDs, and large screens. The researchers reported that, “Screen Based Projection gives inexperienced users the best feeling of immersion” (p. 884). They also noted that the screen based VR was the most liked by subjects because it is “the most natural environment” (p. 884). Patrick, et al. (2000) studied the cognitive maps made by subjects after they had navigated through a virtual amusement park model in desktop VR, a HMD, and a large projection screen. Participants who had experienced the screen environment had lower simulator sickness scores and lower placement error scores than either of the other methods. Lin, et al. (2002) looked at the effects of increasing field of view on presence, enjoyment, memory, and simulator sickness. The team determined that the subjects’ sense of presence and enjoyment increased with increasing FOV until it reached an asymptote at 140 degrees, a very large field of view that is much larger than that typically offered by HMDs. The research also showed a positive correlation between sense of presence and performance on the memory test. These results were echoed by Sutcliffe, Gault, and Shin (2005) who compared a CAVE™ two other large displays: the Interactive Workbench and Reality Room. They found that the CAVE™ was “remembered better, had better usability, and provided a better sense of
presence to its users” (p. 307). Finally, Tan, Gergle, Scupelli, and Pausch (2003) compared subjects’ performances on a mental rotation task and a reading comprehension task displayed on a LCD monitor and a large projection screen. Participants that performed the spatial orientation task experienced a 26% increase in performance over those who had used the LCD screen. In addition, the researchers reported no statistical difference in performance on the reading comprehension task between the two methods. Summarizing these studies, the large field of view offered by projection based virtual reality, like a CAVE™, has yielded superior performance on spatial tasks, better learning in memory tasks, and higher sense of presence and enjoyment experienced by users than HMDs or desktop virtual reality. These research findings combined with the physical and psychological fidelity provided in a VR simulation justify the CAVE’s potential utility as a training environment.

**Uses of Virtual Reality**

In 1995, the National Research Council identified four areas where virtual reality could make the largest potential impact: design, manufacturing, and marketing; medicine and health care; hazardous operations; and training. Since that work was published, significant advances have taken place in all of the areas identified. The areas of training and hazardous operations make nuclear industry training an environment where VR should be a natural fit. For example, simulated radiation environments can be overlaid on computer-generated models of plant equipment to create these training scenarios.
Personnel can safely practice activities in the simulated radiation environment without receiving any actual radiation exposure.

Flexibility, repeatability, spatial fidelity, safety, and the ability to provide context are some of the key features of virtual reality simulations that make it a potential training method for radiation awareness training. The nuclear power plant could be characterized as a hazardous environment. Because of this, proper training takes on additional importance, and research shows that repetition and context are features that improve learning.

Virtual reality systems provide a flexible environment, making it possible to perform tasks that could not or would not be normally performed, basically allowing one to train for both the routine and the unexpected. A single display footprint can be used to create multiple mockups, walkthroughs, or simulations of many things. The application of the technology is only limited by the availability of the models. As was discussed in the last chapter, these are some of the same reasons that instructors select physical mockups as a training environment, but VR provides additional flexibility such as the ability to dynamically change the state of the mockup and the ability to present other simulated data within the context of the mockup.

The training in a VR simulation is designed to be highly repeatable. The scenarios, designed by instructors, can be replayed or reloaded countless times. According to Gagne this is desirable, especially for activities where there are severe consequences for failure. He states,

When the consequences of error are serious, the instructional situation must be designed to produce dependable fault-free performance… The individuals being instructed must learn and practice (as many times as
feasible) the particular procedural skills that are critical to error-free performance. (Gagne, 1985, p.284)

Virtual reality simulations can provide a medium where activities can be repeated so that the error-free performance desired in the nuclear industry can be achieved.

The immersive virtual environment’s stereoscopic, three-dimensional display enables users to view computer-generated data in full-scale, thus accurately representing the spatial relationships between objects. The presentation of data in full-scale creates an authentic and similar training environment, two features that increase transfer of training. Immersive virtual reality provides the user with a significantly larger field of view than desktop systems, which, according to the Human Interface Technology Lab at the University of Washington, increases the user’s sense of presence (Prothero, 1995). An increased sense of presence can lead to increased enjoyment and better memory of the virtual environment and the tasks performed within (Lin, 2002).

Virtual reality offers a safe and controlled environment for the training of tasks that are too dangerous, expensive, or impractical to perform otherwise (Youngblut, 2002). Virtual reality provides an environment where fire, smoke, radiation, or other hazardous environments can be represented without endangering the user. Research by Zimmons (2003) reports that test subjects learn better in virtual environments when there is a perceived sense of danger. The controlled environment enables users’ responses and actions to be recorded and observed. This is another key feature of the virtual environment because it makes it possible to train for events that are impossible to safely recreate on a physical mockup.
Finally, virtual reality enables tasks to be performed or rehearsed in the actual context that workers will experience in the industrial environment. This is important because, as Edmonds (1985, p.2) notes, “Experimentation on active plant components and systems is usually not possible.” Buckley and Caple (1990, p. 135) state,

Pictures and demonstrations can provide trainees with a mental plan or template which will help them to remember the sequence of actions or steps involved in procedural, physical, or manual skills. In addition, as Gagne points out, ‘pictures in particular can aid the learning of manual skills by drawing the trainees’ attention to the external cues that control motor responses.’

Full-scale virtual mockups take this capability a step further by enabling the trainee to view and manipulate equipment and the environment in three-dimensions, much more like the actual work environment.

Lampton, Bliss, and Morris (2002) note two advantages of using virtual environments for human performance measurement tasks. These are “the ability to automatically capture aspects of the user’s performance” and “the ability to provide an observer with comprehensive perspectives of the user’s actions in the virtual environment” (p. 708). These features make the assessment of learning in the virtual environment (VE) somewhat simpler. For example, it is possible to record the user’s motions or paths taken by the user in a VE, and it is also possible to record performance parameters such as time or radiation exposure received in the virtual environment. Instructors can directly or indirectly observe the learners as they train the virtual environment. Footprints such as the CAVETM can accommodate multiple users, which could be a combination of learners, trainers, and observers.
Virtual reality has multiple features that demonstrate its potential as an innovative training environment. Tapping the concepts of similarity and discovery, the virtual training environment can safely simulate dangerous environments, provide a realistic scale environment, and offer a sense of context to the user that cannot be presented in other training environs. The virtual environment maintains many of the features that make the physical mockup environment superior for training with the added capabilities of safety, reduced footprint, and supplementary simulations.

**Virtual Reality Applications**

Virtual reality has historically been used in many fields including entertainment, military training, large data set visualization, and design, but it has been seldom used in nuclear training beyond a few targeted applications. Burdea and Coiffet (2003) describe the uses of virtual reality in the entertainment industry, which includes video games and location based entertainment such as DisneyQuest in Orlando, FL (Figure 4).
The Institute for Creative Technologies at the University of Southern California has been involved in the development of virtual reality training exercises for military personnel using a system called the Mission Rehearsal Exercise (Lindheim & Swartout 2001). One industry which has used VR to study large volumes of data is the oil and gas industry, which uses the technology to pore through seismic and geological data to locate deposits of petroleum (Burdea & Coiffet, 2003). The technology has been successfully used in many design applications such as nuclear power plants (Whisker, 2004), U.S. Navy Ships (Red Dog Entertainment, 2006; US Navy, 2005), and automobiles (Burdea & Coiffet, 2003).

In addition to the areas discussed above, more non-traditional uses are being investigated as the technology becomes more widely used. For example, Jacobs (2003) describes work performed at the University of North Carolina where VR is used to treat phobias such as the fear of public speaking. Donaldson-Evans (2003) discusses similar

Figure 4: Pirates of the Caribbean: Battle for Buccaneer Gold Ride (Disney, 2007)
work in which VR is used as a treatment for Attention Deficit Disorder. Virtual reality has been applied to many fields, and new applications for the technology are constantly being identified.

Due to its multi-dimensional nature, virtual reality is easily applied to tasks requiring accurate spatial understanding, such as design, wayfinding, or understanding spatially varying phenomena. For example, Boud, Baber, and Steiner (2000) discuss the strengths and weaknesses of using virtual reality for assembly tasks after completing an experiment where participants assembled a virtual pump and manipulated rings. Allahyar and Hunt (2003) suggested virtual reality as a means of assessing spatial abilities, as a replacement for tests like the Guilford and Zimmerman Aptitude Survey (1948). Spatial orientation and wayfinding in Virtual Environments are discussed in an article by Darken, Allard, and Achille (1998). The development of this context is discussed in the next section, which details the creation of full-scale virtual mockups.

**Virtual Mockups**

Virtual mockups, full-scale simulated models of buildings and equipment, have many potential uses including design review, familiarization training, and construction review and planning. In the past, scale plastic models or cardboard and plywood mockups were built by designers to lay out systems and communicate designs to customers. Presently, designers create three-dimensional computer-generated product models to perform those tasks. There is a movement underway to use and re-use this
computer generated content for tasks other than design and construction. One of these areas being investigated is training.

In the nuclear industry, worker dose has been reduced and performance has been improved through the use of these models and mockups for planning and rehearsing large-scale maintenance tasks (Punches, 1987; Beck, 1992; Henry, 1995; Baines, 2003). The use of models and physical mockups for task planning and rehearsal has drawbacks, however. Scale models are expensive to create and the small scale often does not show sufficient detail to be useful for anything more than general orientation. For example, the scale model of AP600, shown in Figure 5 on the left, is estimated by the U.S. Department of Energy to have cost approximately $600,000 when it was built in the mid-1990s. Companies still use scale models for familiarization training, as evidenced by the scale models Constellation used for steam generator replacement at the Calvert Cliffs Nuclear Power Plant (Baines, 2003). Full-scale physical mockups can be constructed, as well, although they are expensive to build, and they must be maintained and stored; physical mockups built by the Navy have cost millions of dollars, which explains their transition to virtual mockups (Tatum, Byrum, and York, 1994; Red Dog Entertainment, 2006).

Three-dimensional CAD product models and walkthrough CAD systems offer a potential solution that is superior to the scale plastic models previously used. While the technology exists to present this CAD data in stereo on a desktop computer, it often fails to communicate an accurate sense of scale to the user because users must mentally place themselves within the environment, and people have different levels of spatial ability making this more difficult for some. One possible solution for this shortcoming would be to present a full-scale virtual mockup in one of the immersive virtual reality display
systems, discussed previously, where users are able to physically place themselves in the environment. The evolution of the methods is shown in Figure 5.

<table>
<thead>
<tr>
<th>Past</th>
<th>Present</th>
<th>Possible</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Past" /></td>
<td><img src="image2.png" alt="Present" /></td>
<td><img src="image3.png" alt="Possible" /></td>
</tr>
</tbody>
</table>

Figure 5: Evolution of the Virtual Mockup

Full-scale virtual mockups offer natural navigation; they provide an accurate sense of scale and depth; they can be supplemented with simulation models; and they are easily modified. These features make them an ideal training environment. For example, the virtual mockups created at Penn State’s Applied Research Lab utilize a “point-and-go” motion model in which the user need only point in the direction he or she wishes to travel and push forward on the wand’s joystick to navigate the mockup. This enables the virtual mockups, presented in a CAVE™ display system, to be freely and easily navigated. The user has the option of clamping to the ground with simulated gravity or flying untethered to gain a different perspective. In addition to intuitive navigation, the virtual mockup provides the user with a one-to-one (full-scale) representation of the
Displaying the data in a full-scale stereoscopic environment provides the user with an accurate sense of depth and relative size of equipment, giving the user a truer sense of scale than that provided by a desktop display. Another advantage of the full-scale virtual mockup is that simulations can be loaded with the geometry so that noise can be heard, airflow can be studied, or radiation can be detected, providing additional features not often found in scale models or full-scale physical mockups. Finally, virtual mockups can be quickly updated by loading a new CAD model, which is less involved than removing and reworking physical equipment or plastic models. Virtual mockups experienced in a CAVE™ environment have many features that cannot be duplicated by physical mockups or scale models, so one may conclude that virtual mockups can provide a training benefit similar to, perhaps even exceeding, that provided by the physical mockups.

**Building Full Scale Virtual Mockups**

Virtual mockups can be created in many ways, including creating the mockups from 3D CAD (Whisker, 2004), creating the mockups in graphical modeling software (Burdea, 2003), or using scanning technologies such as close-range laser photogrammetry to create the mockups (Pot, 1997). Each of these methods creates content that can be used in a virtual environment, and portions of a mockup can be created with different methods. Data from the different sources can be combined to create a more complete design.
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 the software, which may then be imported for viewing in a CAVE™ display system. When creating a virtual mockup for display, the models created using a 3-D CAD software package are exported into one of the file formats that the CAVE’s rendering software will recognize. Among the file formats tested over the course of this work were Virtual Reality Modeling Language (VRML) (W3 Consortium, 1995), Open Inventor (Silicon Graphics, Inc., 2006), and Multigen-Paradigm’s Open Flight (Multigen-Paradigm, 2006). Specialized software tools enable the user to translate and manipulate each of these formats. The methodology presented here is one way of performing this translation, but it is by no means the only way.

The virtual mockups discussed in this research were created using a number of different means, including translating the CAD models into a graphical format that can be rendered by the display system using the export feature of the CAD software and additional translation software. The majority of the CAD data used for this research originated in the DGN file format, which is the native output of Bentley’s Microstation CAD software (Bentley Systems, Inc., 2007). Microstation is capable of exporting a number of standard geometry exchange formats including STEP, IGES, and VRML. In the selected translation path, the models used to create the virtual mockups were translated into VRML format. Next, a script translated the files into the 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 format is an ASCII-text based file that may be read directly by the CAVE’s
rendering software, or one additional translation to faster-loading binary formats can be performed. Silicon Graphics’ Performer software (Silicon Graphics, 2007) controls the rendering of the scenes in the CAVE™ display, and the Performer binary (PFB) is the preferred file input to that program. The Explorer software developed at Penn State’s Applied Research Lab is based on Multigen-Paradigm’s Vega (Multigen-Paradigm, 2006) application programming interface (API), and it controls the interaction between the user and the surrounding environment. The process used to create the virtual mockups detailed in this proposal is shown in Figure 6.

Figure 6: Creating Full-scale Virtual Mockups from CAD Models

Creating virtual mockups from CAD models has advantages and disadvantages. In the nuclear industry, reactor designers are working with different forms of 3-D CAD based product models as they design future nuclear power plants. Because of this, 3-D geometric models for future designs are readily available for conversion to the virtual
mockup format, and 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 data can represent the design quite accurately. This accuracy, however, can be a disadvantage (Multigen-Paradigm, 2000). The virtual components are created by generating shapes from many small triangles in a process known as tessellation. Drawing smooth, curved surfaces requires many triangles, while rough faceted surfaces or flat planes require fewer triangles. The high level of detail inherent in the CAD models can lead to a high polygon count, resulting in a slow rendering frame rate thus reducing the immersiveness of a user’s experience since the user has to wait for the screen to refresh instead of that process being imperceptible. This reduction in immersion occurs because the more triangles or polygons the computer requires to create the model, the more information it must process when drawing and displaying each frame.

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 (Okino, 2007) or Right Hemisphere’s Deep Exploration (Right Hemisphere, 2007) may be used to reduce the number of polygons used to render the CAD models. Simplification of the geometry makes rounded surfaces appear more faceted, but polygon reduction is an effective means of increasing frame rate, and CAD models tend to be more detailed than is necessary for most tasks performed in virtual mockups (Shaw & Whisker, 2005).

Because the models cannot currently be rendered in the CAVE™ directly in their native format, file conversion tools must be used, similar to those discussed above. These file conversion tools export models of varying quality. Most tools deliver a final
model that is visually accurate, although the translators generally remove all hierarchical information or additional meta-data leaving only the geometry, which complicates the use of the model in other applications, such as training and maintenance, although it does not make it impossible. Some have pursued ways to translate the geometrical data while maintaining the links to the database that stores the supplemental information, such as a project developing virtual mockups for the Oil and Gas Industry (Corseuil, 2004). While newer translation standards and file formats have improved this weakness, there is still ample room for improvement.

Geometry used for virtual mockups can also be created using digital content creation (DCC) software such as Multigen-Paradigm’s Creator (Multigen-Paradigm, 2006) or Autodesk’s 3D Studio Max (Autodesk, 2007). These software programs can be used to model objects, edit existing models, apply textures to them, or add features such as articulation. The graphical software packages are designed to enable the user to quickly create and manage 3-D geometry. The packages enable the user to manipulate and optimize the underlying database which can increase the efficiency of the rendering of the geometry. This software is generally easier to use than the conventional CAD software, but it does not allow for the inclusion of meta-data that most contemporary CAD software packages do. Graphical software is helpful for creating additional models to make the virtual mockups more life-like, as well as for adding textures to models and optimizing the databases.

Finally, as-built CAD models can be created using close-range photogrammetry technology. Geometry can be recreated by taking a series of pictures (Aoki, 2008) or laser scans from various angles. Computer software reconstructs geometric shapes from
these pictures or scans. In the case of the laser scan system, it reconstructs shapes based on the information from a “point-cloud”, a collection of 3-D points in space. Additional software packages convert these shapes into CAD models. This technology is a fairly recent development and should move toward widespread commercial application in the future with advances in LIDAR (light detection and ranging) and digital camera technology. This could provide a potential method to create virtual mockups of existing nuclear facilities without having to recreate full fidelity CAD models. If software vendors can create a fully integrated package that will convert laser scanning or digital photogrammetry data, pictures, and point clouds into polygonal models, virtual mockups of entire facilities could become a reality; however, a robust version of this capability does not currently exist, although engineers from Electricite de France (EdF) tested a number of methods for laser scanning and CAD model reconstruction during the 1990’s (Pot, 1997).

Full-scale virtual mockups can be created using close-range photogrammetry data, CAD models, and 3-D modeling software. Each of these methods has strengths and weaknesses, and the photogrammetry technique for creating mockups has not yet been tested. CAD provides a high resolution mockup with excellent visual fidelity, but translation to the file formats generally associated with virtual mockups means that much of the meta-data or external information databases are lost. Three-dimensional modeling software provides a quick way to create models for virtual mockups that are optimized for fast rendering, but these models often lack the visual fidelity of CAD. Geometrical hierarchy can also be logically organized and optimized with the 3-D modeling software, which makes the files easier to re-use for other purposes. Finally, close-range
photogrammetry systems could potentially provide a third means for creating the models for virtual mockups, but currently the technology does not allow for accurate tessellation, the organizing of a point cloud into triangles, or creation of models. If this can be done, it could allow for the quick creation of virtual mockups of as-built facilities, such as the existing fleet of nuclear power plants, making the possibility of the development of virtual training mockups for areas of existing facilities more feasible.

**Use of Virtual Reality for Training**

Virtual reality has many attributes that make it a suitable training environment. These features are similar to those suggested in the comparison of virtual mockups, physical mockups, and models, as well as in the discussion of simulations for training in the previous chapter. Again, these features include ease of navigation and the 1:1 scale view of objects. Other features and applications are discussed further in this section.

Wickens (1992) notes factors that influence learning in a virtual environment are motivational value, transfer of the learning environment, a different perspective, and a “natural” interface. Virtual reality tends to be more engaging than conventional training methods, which motivates people to learn since the training environment is more interactive than a lecture or a demonstration because the person has an egocentric rather than exocentric view of the action. Transfer of the learning environment involves exposing the learner to a situation where they can directly experience the topic being learned, such as a field trip, mockup, or simulation, which touches upon the features of constructivism and discovery learning discussed in the previous chapter. Virtual reality
can provide a novel perspective that enables the learner to see material in a different light, which is sometimes all that is needed to enable the learner to extend his or her knowledge. Finally, the interfaces generally associated with VR tend to allow the user to navigate the simulated environment more naturally than those associated with desktop tools such as keyboard and mouse or text-based commands. After fifteen years of innovation, VR simulations can be developed to take advantage of each of these features to enhance learning.

Additional factors are listed by Mantovani (2001). These include experiential and active learning, visualization and reification, learning in contexts that are impossible or difficult to experience in real life, motivation enhancement, collaboration fostering, adaptability, evaluation, and assessment. Of these factors, experiential and active learning, reification, providing contexts, and adaptability are applicable to training radiation awareness in virtual environments. Experiential and active learning have been shown to increase the transfer of concepts to the learner (Mantovani, 2001), since more of the brain is engaged when the learner is motivated and stimulated creating a deeper understanding of the concept. Virtual environments have the ability to reify, or make concrete, complex concepts by presenting material in a different light, such as assisting in the translation from a 2-D concept depicted on the page of a book to the way it behaves in the real world. Providing a context for the material to be trained touches on the concepts of physical and psychological similarity discussed in the previous chapter, which are key factors in learning. Finally, the virtual environments are adaptable in that they can be changed quickly to adjust to changing or emergent needs. Virtual reality should provide a meaningful training environment for radiation awareness and other concepts in nuclear
industry training because of the features described above. It takes many of the strengths of training on physical mockups – similarity, context, realism, motivation – and adds simulation. These features explain why virtual reality should provide a meaningful training environment.

Waller, Hunt, and Knapp (1998) state, “virtual training simulators are effective only to the degree that they enable a user to apply knowledge or skills acquired in the VE to their real-world counterpart” (p. 129). One of the common impediments to learning is the learner’s inability to transfer knowledge from the training environment to the real world situation. This is why similarity between the training environment and the work environment is crucial.

The simplest application where this similarity can be demonstrated is via walkthroughs of architectural spaces in virtual environments (VEs), similar to the one shown in Figure 7. A number of examples can be found. Wilson, Foreman, and Tlauka (1997) ran a group of 48 students through a virtual model of the Astley Clarke building at the University of Leicester presented in desktop VR to test orientation and spatial awareness. After exploring the building in the virtual environment, the students were taken to the real building where they were asked to locate certain features. The results showed that spatial knowledge of the building’s layout obtained in the virtual environment did transfer to the real building. Waller, Hunt and Knapp’s (1998) experiments evaluated subjects’ creation of mental models of a maze using different familiarization methods. The results of their experiments led them to conclude, “With a few caveats, VEs can be an effective medium in which to train spatial knowledge” (p. 142).
As Lathan et al. (2002) describe, “Skills are generally acquired by learning a set of facts about a task and developing appropriate procedures” (p. 403). As the previous chapter detailed, these skills can be developed using simulations of actual environments. Effective simulators may be used to prepare personnel for tasks that may be routine or extraordinary.

It is also worth noting that in any training environment, it is possible to generate decreased performance after training. This situation is referred to as negative training. Lathan et al. (2002) define this concept:
In this case the experimental group exhibits performance that is significantly worse than the control group that did not train in the simulator. In the case of negative transfer, the introduction of a simulator, or modification to an existing simulator, is a detriment to existing training methods (p. 406).

Others believe that it is possible that the reduced effort associated with training in VR can actually impact learning and retention in a negative manner (Wickens, 1992). Wickens notes, “...excessive realism and sensory experience, while ‘natural,’ can distract the learner from focusing attention on the key relations to be mastered” (p. 844). Although it is possible to learn less because of reduced effort, too much effort can also inhibit learning (Wickens, 1992). The learner should be concentrating on the task being performed rather than on the technology being used; however, if the opposite is true, learning can be inhibited. Interface design must, therefore, be a central consideration when developing a VR training application. It is important to find a balance between the two extremes to create a truly effective training environment, and the instructor or developer must be cognizant of the fact that negative training is possible. The iterative process of training development and assessment simplifies the identification and correction of negative training.

Visualization technology enables users to view complex data sets, safely experience hazardous environments, and visit facilities before they are constructed. For example, Salzman, et. al. (1999) discussed the use of virtual reality to aid in learning of complex concepts in physics, describing the creation of “Maxwell World” to teach principles of electricity and magnetism, “Newton World” to teach the laws of motion, and “Pauling World” to teach molecular dynamics. They found that the virtual environment was effective for presenting the complex concepts in three-dimensions.
Their results characterized VR features, concepts, individual characteristics, learning experience, interaction experience, and interactions and trade-offs. The team noted the importance of matching capabilities of the VE and the content presented. One of the key intentions of this work was to assist the student in making the “leap” from a 2-D explanation to a 3-D application. Each of these concepts has a strong spatial dependence in three-dimensions, although they are typically taught using 2-D pictures. Based on the success of this research, one could surmise that other 3-D concepts, such as radiation exposure, could also be trained better in a simulated 3-D environment.

Rose et al. (2000) discuss virtual reality training with respect to transfer and equivalence to real world tasks, finding evidence of transfer from training a task in a virtual environment to performing a task in a physical environment. They found “virtual and real training resulted in equivalent levels of post-training performance, both of which significantly exceeded task performance without training” (p. 494). The researchers noted one significant difference between the subjects’ performances on the real and virtual tasks – real task performance performed after VE training was “less affected by concurrently performed interference tasks than was real task performance performed after training on the real task” (p. 494). The authors continue,

If performance based on virtual training requires less cognitive load than that based on real training it has clear implications for certain types of training. In particular, it would suggest VEs should be used where possible in training people to carry out highly complex tasks in which errors could be either dangerous or very expensive… (p. 507)

Consequently, many tasks performed in the radiation environment have consequences that are dangerous or expensive, again, begging the use of virtual reality as a tool for training tasks to be performed in these situations.
Mourant and Parsi (2002) found that training transferred effectively from stereoscopic VR to the real world for a pick and place task. Performance in groups trained in the real world and virtual reality and tested in the real world task was statistically similar. This research suggests that for simple tasks, there is sufficient equivalence between real and virtual training that it makes no difference that the training environment is simulated. Few complex tasks have been trained in the virtual environment so it is unknown if the phenomena can be extended to larger scale applications.

Mantovani (2001) discusses the lack of research in the use of VR for training and the fact that there is “no common framework for the effective integration of their results” (p. 213). Continuing, Mantovani states, “The investigation of a more complex web of relationship than the one between VR features and learning outcome is especially required when the focus shifts from the training of specific abilities and contents to teaching more abstract contents and higher-level skills” (p. 213). Much of the past training research in VR has focused on desktop applications. As a result, few have investigated training in immersive virtual reality on large projection systems, which are becoming more common.

Examples of VR Training Applications for Hazardous Environments

Features of virtual reality that make it a potential training aid are its ability to present context, its capacity to show scale, and its ability to simulate dangerous environments. A number of examples of VR-based training systems for hazardous
environments exist. Four of these are shipboard firefighting, identification of hazardous materials, utility switchyard training, and mine safety training.

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

The Fully Immersive Team Training (FITT) system was developed to support research and development of distributed virtual environments for team training (Lampton, 2001). The FITT includes a number of advanced capabilities including a motion model, object manipulation, virtual communication between participants, the use of virtual human models (avatars), and data capture and replay. The training system
consisted of a series of computers driving Head Mounted Displays (HMD) that were networked together so that multiple trainees could interact with each other. The trainee received training from manuals, and then the VR trainer was introduced. Once the trainees were comfortable with the two systems, they were immersed in a virtual mission in which they had to work together to successfully complete the mission objective, which was typically a search for hazardous materials. Participants reported that they felt highly immersed in the environment, and researchers noted the participants appeared to be extremely motivated by the training environment.

Denby and Shofield (1999) developed a virtual reality system to train mining personnel to work safely in the mine environment. The system was used to train surface-mine truck drivers in safety practices, to train and test new mine workers in safety inspections, and to train and test mine rescue teams in incident response. The haulage-truck hazard identification system combined realistic mine layouts with dynamic sound, lighting, and physics modeling to reproduce a realistic simulator for haulage-truck drivers, teaching them to identify hazards such as poorly parked vehicles or tailgating situations in the mine. The safety inspection training program presented unsafe situations in the mine, which the subjects had to recognize. It reinforced the training by replaying the scenario with all safety equipment in the proper location. Training was flexible and could be focused on preventing common problems seen in the field. Finally, the mine incident training system was used to train the emergency teams that respond to incidents. Aside from the graphical display, the simulation included a dynamic ventilation model, which was run simultaneously to increase the realism of the training. This system allowed users to be placed in dangerous situations without the risk associated with the
real situation. More recently, Lucas and Thabet (2007) examined similar desktop VR applications for mine conveyer belt safety training.

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

Summary

Virtual reality technology is characterized by a high degree of interaction with multiple senses. The technology can take many different forms including desktop virtual reality presented on a PC monitor, immersive VR presented on a head mounted display, and immersive VR presented on a screen or in a CAVE™. Using these different footprints, virtual reality has been applied in many different areas in the entertainment industry, the military, the medical community, and design.

One of the applications that can be presented in immersive virtual reality is the full-scale virtual mockup. These virtual mockups can be used in design, construction, and training applications. Traditionally, physical mockups and scale models have been
used for these tasks, but advances in 3-D modeling technology make it possible to create full-scale virtual mockups. The virtual mockups are generated from 3-D CAD models, 3-D modeling software, and close-range photogrammetry. Each of these methods has specific applications in which it can be best applied, but the outputs from the three methods can be combined in a single mockup if necessary.

The VR technology has many features that make it suitable for training including the ability to create context for the task being trained, the ability to add simulation models to the geometry, repeatability, a natural interface and interaction, and its ability to generate interest in the learner due to the novel training environment. Of these, the creation of context is important since educational psychologists believe that similarity between the training environment and the real world environment is paramount to transfer of training. The addition of simulation models makes it possible to create simulated hazardous environments that have many features of the actual hazardous environment, without the danger. Some of the hazardous tasks that have been trained in VR include coal mine safety, hazardous material identification, power plant switchyard maintenance, and shipboard firefighting.

Since virtual reality has been successfully applied in other training contexts, it follows that it should also be applicable to radiation awareness training for the nuclear industry. The nuclear industry’s current training programs are described in the next chapter.
Chapter 4

Training in the Nuclear Industry

The training performed at nuclear power plants takes many forms. Among these are reactor operator training, equipment operations training, radiation worker training (RWT), and plant access training (PAT). Each of these courses is driven by different requirements, and many different training methods are used. Because of the significant consequences of failure or mistakes, training is one of the most important activities undertaken by utilities operating nuclear power plants. The types of training, training methods, requirements governing training, and the development of training programs for the nuclear industry are described in this chapter.

Historically, utility maintenance training was performed by placing newer personnel, apprentices, with seasoned personnel, referred to as journeymen. Length of service and perceived capability displayed by the journeyman were the only qualifications needed to instruct the apprentice. Instruction basically took the form of “watch and learn.” However, increased technology and demands on personnel have led to more advanced forms of training because years of apprenticeships were no longer practical. These activities adapted into more formal on-the-job training, classroom training, and laboratory training (Curling, 1985).

The training environment in the nuclear industry changed significantly after the accident at Three Mile Island (TMI) in 1979. The importance of personnel training was highlighted by the reactor operators’ responses to the series of events (Kemeny, 1979).
Training of personnel was brought to the forefront as the Nuclear Regulatory Commission (NRC) and the nuclear industry examined the lessons learned from the accident.

As a result, the Institute for Nuclear Power Operations was formed by the nuclear industry. Russ (1982) describes the formation and missions of the organization. The author refers to INPO as a “non-profit, independent organization, created after TMI by the nuclear utility industry…founded to assist utilities in achieving a high level of excellence in safety in nuclear power operations” (Russ, 1982, p. 635).

Two of INPO’s missions relate to training. INPO looks for evidence of a systematic development process, and then accredits the organization. It runs the accreditation program, and it develops and provides training guidelines for the industry. As Russ (1982) states, “accreditation involves in-depth evaluation of a training organization and the programs it conducts to determine whether it can produce individuals qualified to perform their assigned jobs” (p. 640). INPO’s accreditation process involves four steps: a self-evaluation by the utility, a site visit by a team of industry personnel, preparation of an accreditation report of findings and recommendations, and a decision by the accreditation board (Russ, 1982). Once a training program is accredited, it is assumed that the utility has met industry-wide standards for effective training, and consequently NRC oversight is minimal for accredited programs.

The second function of INPO is to assist the industry with developing guidelines for the training programs. Guidelines for the training of multiple specialties have been drafted, including control room operator, control room supervisor, shift technical advisor,
electrical and mechanical maintenance personnel, and radiation protection technicians. These guidelines were based on job and task analyses, event analysis, and experience gained from prior evaluations (Russ, 1982).

Booher (1985) describes the NRC nuclear power plant training and qualifications policies that were created as a result of the 1979 accident at the Three Mile Island nuclear power plant. The NRC issued a policy statement (10CFR50.120) known as the training rule which defined acceptable training practices in the nuclear industry. An acceptable training program was described as having five essential elements: a systematic analysis of jobs to be performed, learning objectives derived from the analysis which describe desired performance after training, training design and implementation based on the learning objectives, evaluation of training mastery of the objectives during training, and evaluation and revision of the training based on the performance of trained personnel in the job setting.

Nuclear power plant training currently takes many different forms. Training activities include tabletop exercises, role playing, Computer Based Training (CBT), and mockup training. Buckley and Caple (1990) define these training methods and discuss strengths and weaknesses of each. The authors describe simulation/role playing as “the presentation of job and task activities which as near as is practicable replicate the essential features of the real situation…trainees are required to use equipment, solve problems, follow procedures, and act out roles as if they were performing the job for real” (Buckley & Caple, 1990, p. 163). They also note, “Simulation exercises are based on the application of skills to machinery and equipment. They are best used when access to the real equipment is difficult and when the consequences of error could be costly or a
danger to life” (Buckley & Caple, 1990, p. 164). Based on this statement, simulation and role playing should be an excellent training method for nuclear power plant training given the difficulty associated with accessing areas of the plant as well as the consequences of poor performance. Unfortunately, this type of training is not as widespread as it could be.

Widen and Klemm (1986) describe a partnership between Commonwealth Edison (now Exelon) and Westinghouse, which developed Computer Based Training materials. They describe the CBT system as being divided into hardware, software, and courseware. The authors note that the priorities for the partnership were to develop CBT systems for Nuclear General Employee Training (NGET) for all plant personnel and re-qualification training for operators. They summarize their work in development and implementation by saying, “the inception of the CBT library is too recent to quote empirical gains in either training mastery or time efficiency…however, one very meaningful result can be gleaned: students enjoy and utilize CBT” (Widen & Klamm, 1986, p. 647). The students most likely enjoyed the CBT because it was more dynamic and interactive than the classroom methods that had been used to-date.

Painter (1988) discusses an early use of CBT at the Savannah River Plant in South Carolina. The author describes the evolution of training at the site from classroom lectures using a blackboard, to videotapes produced in-house, and finally to computer-based training. CBT is reported to be easier to produce and change, and the authors laud the introduction of the video disc technology. At the time, the CBT was used to supplement classroom instruction.
When Painter’s research was performed, the training required specialized computer hardware, but now most systems operate on common PC workstations. During site visits at two nuclear power plants, this author had a chance to view the CBT training systems currently being used. The current CBT systems are rich with media and include animations and videos to make training more engaging and interesting to the user. While this is true, theories presented in Chapter 2 hold that this method does not reach all learners equally. As Furgang (1986) states, “such training [videotapes and multimedia], almost by definition, provides only cognitive learning. No one has ever learned to ride a bicycle while watching a videotape or reading a text on the subject” (p. 59). For this reason, many utilities use mockups for hands-on training.

Perhaps the most well-known training environment in nuclear power plant is the use of the control room simulator, shown in Figure 8. Each nuclear power plant has a replica control room simulator through which the teams of operators rotate every few weeks. Simulator training of operators is designed to ensure the proper response to normal and abnormal operations. After the accident at the Three Mile Island Unit 2 plant in 1979, the nuclear industry placed more emphasis on simulator training for operators because the NRC required it based on some of the questionable responses by the operators to information they were receiving from plant sensor data.
Brewer and Hoffman (1985) discuss the training programs for licensed operators, shift technical advisors, and managers and engineers used by the Tennessee Valley Authority (TVA). The authors cite three driving factors for the development of simulator training for personnel: the NRC’s response to the TMI accident, the industry’s response to the formation of INPO, and the needs of the operators and personnel based on feedback from operators and management.

Each simulator training program uses a specific lesson plan or exercise guide to focus the training to meet certain objectives. Simulator training is designed to build on items learned in classroom training sessions as well as previous simulator experiences to assist the operators in making the transition from classroom concepts to application in the plant environment. Some training sessions begin with a demonstration of plant response
in the simulator, and then include a walk through the procedure with the instructor. Once
the walkthrough has been completed, the students are asked to follow the procedure and
respond to the transient. The need for specific training can be assessed in many ways:
“economic consequences of errors (equipment damage, purchase of replacement power
due to lost generation), risk to plant personnel (real or projected), and risk to the general
public (projected)” (Brewer & Hoffman, 1985, p. 127). The control room operator
training on the simulator and in the classroom is an example of multimedia training that
assists the operators in making the transition from theory to practice.

Nuclear power plant personnel training extends beyond control room simulator
training. For example, Price and Dutch (1991) described three activities used for training
nuclear power plant personnel at a training center in the U.K. as a part of a course titled
“Introduction to Nuclear Plant Theory.” The first activity dealt with locating surface
contamination with a survey meter by placing radioactive (thorium) lantern mantles
inside of the pockets of protective clothing. Using plastic absorbers, the trainers were
able to vary the readings on the trainees’ detectors. The activity taught the personnel to
be cognizant of allowable contamination levels, proper mitigation procedures, and the
reading of survey instruments. A second activity instructed the students on proper
classification and procedures associated with radiation controlled areas and
contamination controlled areas. The activity was designed to be a competition between
two groups of participants to stimulate the trainees’ competitive natures, thereby turning
a “boring” activity into one that would be more memorable. The final exercise described
by the authors was an activity developed for training Senior Authorized Persons. The
Senior Authorized Person is a member of the operations shift team who is “authorized
separately to issue safety documents detailing isolations taken, and the precautions required to avoid electrical and mechanical hazards” (Price & Dutch, 1991, p. 166) Another duty of the Senior Authorized Person is to issue Radiological Control Documents (RCD) (Radiation Work Permit in the US) for work in controlled areas, which details the radiation hazards and associated precautions. The personnel are required to complete an exercise where they create a RCD under the supervision of a tutor. Course members must practice radiological safety rules; demonstrate ALARP –As Low as Reasonably Practicable - (As Low As Reasonably Achievable (ALARA) in the U.S.) principles; conduct the required radiation surveys; record, communicate, and explain survey results; and properly complete the RCD paperwork. In addition to the three activities described above, the authors noted that in the process of the work, they reviewed a number of “source simulators and remote controlled instruments” (p. 167). They report that at that time, 1991, there was no viable simulation capability that could be used for radiological training; however, these simulations now exist in the form of virtual reality simulations and simulated radiation meters such as the Teletrix.

Training can be routine and scheduled, or it may occur “Just-in-Time” to meet emergent training needs or requirements. For example, according to Zuercher (1999), “North Anna also uses just-in-time (JIT) training to help workers become familiar with tasks, particularly those that are performed infrequently or require special skills or precautions. The training may include hands-on experience on equipment mockups” (p.6). A training activity using a mockup is depicted in Figure 9. These mockups may be full-scale or reduced scale as in the steam generator models mentioned later.
In addition to being various sizes, mockups may be system-specific or generic. System specific mockups appear just as the piece of equipment would in the plant, while generic mockups are typically a similar piece of equipment to that in the plant without the context of the systems and piping surrounding it. Zuercher notes,

We have a mockup of charging pump seals and do just-in-time training before a crew works a seal leak. We can tear the seal apart, put it back together and get familiar with the procedure before we have to do the real job in a radiological area. It helps us make sure we can do the job safely and efficiently (p. 6).

Figure 9: Training Role Playing Exercise

Edmonds and Meyer (1985) discuss the use of mockups for training.

Given these limiting factors, it was decided to invest in critical plant specific equipment and perform equivalent tasks at our training center. By
doing this, the instructor is given more control over the experience than with in-plant OJT [on-the-job training]. Such intense ‘hands-on’ training programs [make] it possible to provide the individual with an extensive amount of experience in a relatively short amount of time. By building on previous experience it is then possible to introduce increasing levels of complexity into the practical exercises which increase the realism of the exercise (p.2).

These applications point out the utility of mockup training and the importance of practical experience for error free performance. Virtual reality may potentially be applied in these situations.

**Nuclear Power Plant Training Requirements**

Because safe operation of nuclear power plants is essential, operator training programs for these plants are governed by many requirements. Generic guidelines are established in the Title 10, Part 50 of the Code of Federal Regulations (10 CFR 50.120) and Part 55 (10 CFR 55). Additional guidelines appear in each plant’s technical specifications, and Safety Analysis Reports (SAR); American National Standards Institute (ANSI) standards; Nuclear Regulatory Commission (NRC) regulation guides (Reg. Guides), letters, and NUREGs; and Institute for Nuclear Power Operations (INPO) guidelines and accreditation programs. For example, the complex process of nuclear general employee training (NGET) is shown in Figure 10.
A presentation delivered to new utility training managers by INPO summarizes the training requirements for nuclear power plant personnel (INPO, 2005). Title 10, part 55 of the Code of Federal Regulations (10 CFR 55.120) establishes the requirements for training and qualification of power plant personnel. The training programs must be developed using the systems approach to training. The personnel that must undergo this training are:

- Licensed operator
- Non-licensed operator
- Shift Supervisor
- Shift Technical Advisor
- Instrument and Control Technician
• Electrical Maintenance Personnel
• Mechanical Maintenance Personnel
• Radiological Protection Technician
• Chemistry Technician
• Engineering Support Personnel

According to INPO (2005),

The training program must incorporate the instructional requirements necessary to provide qualified personnel to operate and maintain the facility in a safe manner in all modes of operation. The training program must be developed so as to be in compliance with the facility license, including all technical specifications and applicable regulations. The training program must be periodically evaluated and revised as appropriate to reflect industry experience as well as changes to the facility, procedures, regulations, and quality assurance requirements. The training program must be periodically reviewed by licensee management for effectiveness. Sufficient records must be maintained by the licensee to maintain program integrity and kept available for NRC inspection to verify the adequacy of the program.

Title 10 CFR Part 55 establishes the requirements for operator licensing and requalification. The document encourages the licensees to use the Systems (or Systematic) Approach to Training (SAT) for both training programs. Each training program must be reviewed and approved by the Nuclear Regulatory Commission.

The Nuclear Regulatory Commission’s REG GUIDE 1.8 “Qualification and Training of Personnel for Nuclear Power Plants,” establishes the actual guidelines followed for training programs at nuclear power plants. The document states, endorses, and modifies some of the requirements of various ANSI/ANS standards. Versions of the guide cover management, technical, and operations positions.

The NRC’s assessment criteria are set forth in NUREG-1220 (NRC, 1993). This document provides reviewers with a guide for the review of utilities’ training programs. The reviewer assesses the suitability of the training program by observing training
activities, interviewing instructors, managers, and personnel in training, and evaluating the implementation of the systematic approach to training (SAT). The NUREG documents suggested timelines for the review process, potential interview questions, and checklists for assessment. The document is designed to provide a prescriptive guideline for the reviewer to follow when performing the assessments.

A memorandum of agreement established between the NRC and INPO assists plants in maintaining compliance with the training regulations by undergoing an INPO-sponsored accreditation process. The NRC assesses the effectiveness of industry's training and qualification programs by observing selected INPO documents and activities, conducting operator initial licensing exams, auditing, monitoring, and/or conducting exams, and monitoring plant events involving personnel errors.

**Basis for Nuclear Power Plant Training Programs**

According to the National Academy for Nuclear Training (2002),

The goals of successful training and qualification programs are to produce and maintain well-qualified, competent personnel to safely and reliably operate, maintain, and improve the performance of nuclear power stations. Continuing training is used to refresh and improve the application of knowledge and job-related skills to meet management’s expectations for individual and station performance (p. 5).

Today’s training activities are designed using SAT, which was adapted by the nuclear industry from military and aerospace training programs. Wilkinson (1995) describes the SAT as a “logical, repeatable, flexible, and pragmatic approach to training” (p. 181). Seels and Glasgow (1998) state that instructional systems design (ISD), a superset of SAT, is “based on the premise that learning should not occur in a haphazard
manner, but should be developed in accordance with orderly processes and have outcomes that can be measured,” (p. 7) and it “brings objectivity and orderliness to the process of planning instruction so that the quality of instruction is assured” (p. 18).

SAT or ISD requires defining what is to be learned, planning activities that will allow learning to occur, measuring learning to determine if objectives were met, and refining the activity until objectives are met (Seels & Glagow, 1998). The five steps of the SAT, depicted in Figure 11, are analysis, design, development, implementation, and evaluation. This process is sometimes referred to by the acronym ADDIE. In the initial stage, a needs analysis is performed, task analyses are performed, and the skills that require training are selected. In the second stage, the trainee’s previous knowledge is assessed, learning objectives are recorded, job performance measures are selected, and a training plan is developed. In the third stage, development, training methods and learning activities are specified, training materials are developed, lesson plans are created, and pilot training sessions are held. During the implementation stage, the training is conducted, trainer and trainee performance are tracked, and results are documented. Finally, the evaluation phase requires that information be collected and analyzed, quality indicators be tracked, and corrective actions be taken to improve training. The SAT is an iterative process that relies on feedback collected during the evaluation step to assist the developers with improving the training program.
In 1985, the SAT was applied to maintenance training for personnel at the Salem Nuclear Power Plant (Edmonds & Meyer, 1985). Using work orders and inspection orders, the developers created task lists for the maintenance activities that were performed at the plant. The list was compared to the master INPO list, and subject-matter experts (SME) were consulted to ensure completeness. During the design phase, training programs to develop the specific skills listed in the task analyses were created. The authors note that some of the objectives can be achieved using classroom training, while others require hands-on, mockup-based activities. At the time the article was published, Salem used performance-based training activities. During the development phase of SAT, the instructors created “performance-based instructional objectives,” which provide the basis for lesson plans. Also during this phase, test questions and qualification cards were generated. New training programs were developed and existing training programs, originally developed for fossil plants, were updated and implemented. According to the authors, the maintenance training programs implemented consisted of more than 60-percent hands-on practical training activities. Finally, the authors used a formal training review committee created from plant supervision and training personnel. These expert personnel review performance and recommend changes to improve the
training program. The program successfully applied the systems approach to training to the maintenance training programs at Salem.

**Development of Nuclear Power Plant Training Programs**

As was discussed before, the Institute for Nuclear Power Operations (INPO) provides oversight for all training activities in the nuclear industry per the agreement stated in the previous section. INPO publishes a series of Academy Documents (ACADs) that guide the utility personnel in the development of training programs. All training programs are developed using the Systematic (Systems) Approach to Training (SAT), an approach based upon the basic theories of Instructional Systems Design (ISD). The SAT, ISD, and ADDIE will be discussed further in this section.

According to Smith and Ragan (2005), instructional design can be defined as the “systematic and reflective process of translating principles of learning and instruction into plans for instructional materials, activities, information resources, and evaluation” (p. 4). The authors note that the instructional designer’s job is to answer three basic questions:

- Where are we going? (What are the goals of instruction?)
- How will we get there? (What are the instructional strategy and the instructional medium?)
- How will we know when we’ve arrived? (What should our tests look like? How will we evaluate and revise the instructional materials?) (Smith and Ragan, 2005, p.8)

Appendix A of ACAD 02-001 describes the essential elements of the systematic approach to training. SAT is defined by INPO as a “proven, structured method for
efficiently producing job performance-based training that addresses personnel and organizational needs and performance deficiencies. The training outcomes contribute to improved job performance and professional development” (INPO, 2003, p. A-1). The SAT process encompasses the activities of analysis, design, development, implementation, and evaluation (ADDIE).

The skills and knowledge required by the trainee are defined during the analysis phase of the SAT. Activities performed during the analysis phase include performing job analyses to select job tasks for which training is required, conducting task analyses to determine how tasks are performed and what knowledge is required for the task, consulting of subject-matter experts (SMEs) to define proper task performance, and surveying potential performance measures that can be used to evaluate the effectiveness of the training (INPO, 2003).

During the design phase, information collected during the analysis phase is used to specify the knowledge and skills that the training will develop in the trainee. Activities during the design phase include describing the learning objectives that tell when, what and how well the trainee must perform, preparing performance tests to measure the adequacy of the trainee’s performance, developing methods to observe and measure trainee performance, and determining the setting in which training will be conducted based on the requirements of knowledge and skills to be acquired (INPO, 2003).

The implementation phase focuses on putting the training program into operation. Key activities during this phase include performing the training activity, training of instructors and SMEs, and collecting feedback on content and delivery, which may include the effects of training on personnel and plant performance, reinforcement of
management expectations, trainee test performance, and critiques of training (INPO, 2003).

Finally, the evaluation phase ensures that the training is generating satisfactory results. Activities that may be performed during the evaluation phase include analyzing and trending feedback collected during training and analyzing job performance feedback to determine training program effectiveness and to identify training program challenges (INPO, 2003).

There are varying degrees of execution for the ADDIE process. Not all training tasks require an in-depth look at all steps of the process. INPO notes

…if a task is relatively simple and carries little risk of personnel or equipment damage, the use of the systematic approach to training in determining the training and evaluation needs for the task can be streamlined… If, on the other hand, the task carries a greater level of risk for the station or the people, or if it is more complicated, the level of the systematic approach to training should be more detailed (INPO, 2003, A-1).

Generally, INPO does not specify which method must be used for training, but they do highlight operational experience and best practices that utilities might consider when designing their training programs. Utilities also share information between organizations through exchange programs and site visits. These exchanges help the training staffs to design new activities and new mockups to improve the training they offer at their home plant.

For immersive virtual reality to be accepted as a valid component of a training program, the training concept developed for the virtual environment must be designed with SAT in mind. The tasks and concepts to be trained must be carefully vetted to determine whether they are appropriate for training using activity-based methods. The
training must be developed in an iterative process with evaluation and re-design to create the best training environment possible. If the evaluations prove to be worthwhile, the trainer will be able to add a flexible tool where radiation exposure can be safely simulated.

Use of Physical Mockups for NPP Training Activities

According to Maletskos (1995), workers who receive training on mockup equipment are allowed to work in a “clean” environment that prepares them to work more efficiently in a radiation area. This training allows workers to ask questions, become familiar with the maintenance and inspection process, and work out any kinks before entering the radiation areas. Mockups are used for work such as installing ultrasonic scanners, temporary shielding, removing or replacing control-rod drive mechanisms, and valve disassembly and reassembly.

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

Improving Performance using Mockup Training

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

**Steam Generator Replacement**

Many utilities have used mockups to prepare for steam generator replacement because it is an activity that must be planned very well in order to execute during an outage with minimal delays or effect on completion. Because the steam generator is a radioactive component, the task requires careful management of the workers’ radiation doses. The activity involves cutting and removing many connecting pipes, supports, and equipment that are potentially contaminated. As a result, utilities have used mockups or scale models for planning this complex task.

Three examples are highlighted. Two applications discuss the use of full-scale physical mockups, which resulted in significantly lower collective radiation doses than published results from previous steam generator replacement evolutions. The third
application discusses the use of a small-scale model used in preparation for the same activity, but the dose savings were not published for this example. Full-scale virtual mockups could potentially be used in place of these in the future.

**North Anna Steam Generator Replacement**

Henry (1996) describes the steam generator replacement project at North Anna Unit 1 in the mid-1990’s that made significant use of a physical mockup to plan the work and to reduce radiation exposure to workers. Steam generator replacement is a complex undertaking, that is both labor-intensive and radiation exposure-intensive. The mockup training program was used to address the radiation dose reduction (or ALARA) principles of minimizing time, maximizing distance, and optimizing shielding in order to reduce radiation exposure.

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

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

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

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

A 40’x 40’ x 30’ building housed the physical mockup. The mockup consisted of a full-scale steam generator channel head and lower support structure. A full scale mockup of the transition cone was manufactured and installed on the mockup. In order to simulate the operational and environmental constraints, scaffolding and shielding were erected around the mockup. Personnel wore the appropriate protective clothing and operated under the expected environmental conditions such as elevated temperature. Activities that were selected for the mockup training were performed twice on the mockup prior to their performance in the field (Henry, 1996).

Henry provides a list of lessons learned from the mockup training activities:

• The program should be developed jointly between the utility and the contractor so all affected organizations are part of the process
• Continuity between the workers and their radiation protection team should be maintained. The radiation technicians that work with the personnel on the mockup should be the same ones they will work with in the field.
• Mockup training should occur as close to the actual task performance as possible to prevent workforce attrition.
• The better the mockups recreate the work environment; the better prepared the workers that train on the mockups will be for their real-world task.

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

**Palisades Steam Generator Replacement**

Beck et al. (1992) state, “One of the most significant aspects of the RPP was the extensive use of mockups to train the workforce to perform activities related to their steam generator replacement” (p. 1297). The steam generator channel head and coolant system piping were mocked up in full-scale. The mockups were used to familiarize craft personnel with the work activities they were to perform, as well as to evaluate and refine the activities prior to their actual completion. Using the mockup, the craft personnel were qualified to perform the following activities: “RCS [reactor coolant system] system pipe cutting/machining, RCS narrow gap welding, RCS pipe end decontamination, SG primary nozzle water shield installation, RCS pipe internal shielding installation, and RCS NGW purge dam installation” (Beck, 1992, p. 1297). Use of the mockup resulted in a US Nuclear Industry record for the lowest accumulated radiation exposure (487 man-rem) during a steam generator replacement.
Calvert Cliffs Steam Generator Replacement

Baines (2003) reports on the use of 1/16th scale models to plan work associated with the steam generator replacement at Calvert Cliffs Nuclear Power Plant. Two models of the steam generator were built to demonstrate changes between the old steam generator being removed and the new steam generator being installed. Baines states, “The new and old models are used mostly for planning purposes, providing project personnel with a visual, 3-D model that gives a good idea of how components might interfere with each other during removal and installation” (p. 40). When asked about the cost-effectiveness of the scale model, Baines notes,

I can conservatively say that we probably will save the cost of the model through planning improvements over both the Unit 1 and Unit 2 steam generator replacement outages. There is not an easy correlation of direct savings associated with the training use of the model (p.40).

According to Banes, the workers at the plant were pleased with the colorization, detail and ease of viewing of the model. The author also mentions a model of the reactor vessel, which Constellation used for training.

Other Applications

Many tasks and concepts in the nuclear industry require training. The activities that are trained are typically those that require significant planning and coordination such as reactor vessel head replacement or steam generator replacement, and the concepts can be basic or complex, ranging from simple valve maintenance to criticality. Criticality safety (Knief, 1986), control rod drive maintenance training (Werres & Thornton, 1990),
and Radiation Protection Training (Price & Dutch, 1991; Croft & Hudson, 1982) are examples of training activities.

Shelter and Slaga (1985) describe pump maintenance training at the Millstone nuclear power plant. They visited several utilities to observe pump maintenance training since “improper maintenance that causes a pump to malfunction can result in safety concerns and costly downtime and repairs” (Shetler & Slaga, 1985, p. 403). They describe the use of on-the-job training for the pump maintenance, but they state, “On-the-job training must be supplemented with off-line, hands-on, equipment-specific training, where basic theory of design and operation can be added to enable effective maintenance” (p. 404). Many utilities, such as the ones discussed in the next section, have hands-on laboratories where these concepts can be trained in such a manner.

**Observation of Nuclear Power Plant Training Activities**

The training activities of three utilities were observed by this author in order to determine the types of tasks training programs cover, while the training activities of a fourth utility were discussed with the utility’s training manager. Much of the discussion centered on the utilities’ use of mockups for training.
Limerick Generating Station

The Limerick Generating Station in Limerick Township, PA is owned and operated by Exelon. The site houses two GE Boiling Water Reactors. This author visited their training building in 2003.

An instructor from the plant discussed methods used at Limerick for Radiation Worker Training, Advanced Radiation Worker Training, and General Employee Training. The instructor provided a number of helpful training materials that cover the training of supplemental radiation protection (RP) personnel, a format used for development of dynamic learning activities, a representative procedure used for on-the-job training (OJT) or Task Performance Evaluation (TPE), and an example of a retraining/reinforcement procedure for radiation protection personnel.

Limerick uses a Teletrix system to simulate radiation environments for training purposes. The components of the Teletrix system are shown in Figure 12. The system’s survey meters respond to an artificial count rate set by the instructor using an RF transmitter (Teletrix, 2005). To use the system, the instructor turns the dials on the transmitter and the appropriate reading is displayed by the survey meter. A number of simulated meters are available.
In addition to the Teletrix system, the training lab this author visited also housed a physical mockup of a small pipe loop. The loop is used to demonstrate the basic procedures of surveying and breaching closed systems. The loop, the only mockup seen during the visit to Limerick, is shown in Figure 13. Limerick uses additional mockups for training, but these were not on display at the time of this author’s visit.
Much of the job training performed at Limerick is based on classroom review and pairing experienced personnel with inexperienced personnel (OJT). According to Warren, task review during the ALARA pre-job briefing is now the norm. Personnel will typically walk down the work area sometime prior to the job being performed. The ALARA briefing and walk down will often specifically point out hold points in the procedure where radiation protection technicians or personnel are to be involved in order to limit unnecessary radiation exposure.

Additional training activities at Limerick were discussed. One of the ways they reinforce classroom learning is through dynamic learning activities (DLA). These activities are designed to improve the knowledge and skills of advanced radiation workers and to decrease the likelihood of a “human performance related event.” The DLAs are scenario-based training exercises built around simulated activities. The

Figure 13: Static Training Test Stand
scenarios are often based on events that have occurred at other plants in order to prevent similar occurrences at Limerick. These types of learning activities could offer a potential test environment for training with virtual mockups.

**Susquehanna Steam Electric Station**

The Susquehanna Steam Electric Station (SSES), a Boiling Water Reactor, near Berwick, PA operates two facilities that house mockups for training. The Learning Center houses a number of mockups, and the West Building houses the Performance Simulator.

In addition to the mockups at the Learning Center and Performance Simulator, SSES also has numerous classrooms, hands-on training labs, and the required full-scale control room replica simulator. The control room simulator and classrooms are housed in the Learning Center. Classroom training for chemistry, electrical, and mechanical specialties is also held at the Learning Center. In addition, a full scale mockup of the area under the vessel has been reconstructed for control rod drive maintenance training.
The closed cooling water (CCW) mockup and the valve trailer containing a series of valve mockups are also used for practice activities. The CCW mockup, shown in Figure 14, is a large, complex skid with multiple pumps, a tube in shell heat exchanger, and many valves. The mockup is currently used for training personnel in electrical maintenance, valve maintenance, and proper work procedures. The valve trailer contains examples of many of the valves that are used in the plant. The valve trailer provides a hands-on training environment where the valves can be assembled and disassembled.
At SSES, the Performance Simulator is a multi-station training facility. Currently under construction, the laboratory will eventually include 12 hands-on learning stations. Example stations, shown in Figure 15, are used to train employees in electrical panel maintenance, radiation dose awareness and procedure reading, and housekeeping. Behind the physical mockups, large pictures of areas of the plant were fixed to the wall to attempt to add context to the physical equipment to enable the workers to suspend belief that they were in a training environment. This is an area where virtual reality provides a superior sense of context since the view of the plant is dynamic rather than static.

Figure 15: SSES Performance Simulator Stations

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

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

The activities are designed to reinforce many work practices including peer checking, the STAR (Stop, Think, Act, Review) principle, proper 3-way communication, procedure use, evolution termination criteria, and discussions of operating experience. These are the types of activities that could potentially be trained in the virtual environment.

**Perry Nuclear Power Plant**

The Perry Nuclear Power plant’s training program has been featured in a number of publications including the Nuclear Professional and Nuclear News (McCullough, 2004). The Boiling Water Reactor is owned and operated by First Energy Nuclear Operating Co. (FENOC), and it is located in Perry, Ohio on Lake Erie. This author toured Perry’s training mockups in June of 2004.

Like all nuclear power plants, Perry has a full scale physical replica simulator for the control room that is laid out in a more “wrap-around” fashion, typical of the most recent generation of BWR operating in the US. An operations training instructor demonstrated ways in which many operators utilize the replica simulator at Perry. Tactile feedback is important to the operators when performing maneuvers, making the control
room simulator a difficult candidate for re-creation in virtual reality, since haptics technology that mimics the sense of touch is still being developed.

Perry also has a large fire brigade training facility. The facility has a large tower used for ascending and descending training, a burn building, a tank to simulate gas fires, a transformer to simulate transformer fires, and three trailers connected used for self-contained breathing apparatus (SCBA) training. The SCBA facility is a training “maze,” a system of obstacles designed to give trainees an idea of how to navigate confined spaces with their breathing apparatus. The SCBA mockup is another facility that relies heavily on the sense of touch and feeling, and therefore, would not lend itself to recreation in VR at the present time.

The maintenance training facility known as the “Loop of Excellence” contains a number of mockups, shown in Figure 16. Some of these are related to the large flow loop, while others are simply small mockups of areas of interest. These smaller mockups include the control rod drives and the reactor water cleanup pump room. The large mockup has a separate control room where the status is controlled. The facility also houses a live electrical panel training mockup.

When the mockup is used for training, a dose map of the area is given to the trainees. The dose map contains simulated radiation “measurements” at a number of locations. While the trainees typically wear protective clothing and dosimetry, the equipment is basically for show, providing no valuable feedback on radiation exposure or contamination. The mockups appear to be a significant part of their training program.
Perry also uses a mockup, depicted in Figure 17, to train personnel to dress in protective clothing and to access the protected area. The plant has a physical mockup of all of the equipment required to access the plant - the Radiation Protection desk, a binder of Radiation Work Permits (activities and instructions) and dose maps, the dosimeter/RWP login, and the entry turnstiles. Once inside, a few piping systems with mannequins dressed in protective clothing demonstrate work practices. The exit process is also mocked up with a step-off pad, a Personal Contamination Monitor (PCM), a Small Article Monitor (SAM), and an exit turnstile. These mockups were used for access
training and radiation worker training. Some utilities such as Iberdrola in Spain have performed similar access training using virtual reality (Felipe, 2003).

Another member of Perry’s training staff demonstrated Perry’s interactive computer based training used for training and requalification on the procedures for dressing out and accessing the protected area – selecting an electronic dosimeter, logging in on an RWP, donning and removing protective clothing, etc. The system is a Windows-based multimedia presentation, a combination of pictures and digital video. The videos illustrate common mistakes as well as proper procedures. (Kmiecik, 2004).

San Onofre Nuclear Generating Station

Robert Sandstrom, a training manager from San Onofre Nuclear Generating Station (SONGS), discussed his utility’s activities, which include the use of physical mockups (Sandstrom, 2002). SONGS uses mockups for survey training,
decontamination, plant entrance and exit, introduction to plant rules, and the proper use of tools. Since steam generator maintenance is a high dose-activity, a mockup of the steam generator manway is used to train workers to perform nozzle jumping activities. Mockups are also used to train personnel on the proper use of robotic tools. In addition, SONGS uses a mockup to train workers to perform electrical breaker maintenance. Finally, they train personnel to improve human performance such as the STAR principle and proper reading of procedures.

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

**Observations**

The four training programs are subject to the same sets of guidelines, but it is apparent that each meets those guidelines in very different ways. Perry and Susquehanna have a significant investment in the use of physical mockups, while the use of mockups at Limerick and SONGS was less apparent. The performance simulator at Susquehanna is but one example of providing utility personnel with an engaging, hands-on environment where they can rehearse common tasks and be trained in proper work practices under the close watch of the training staff and fellow workers. This environment effectively trains personnel who have multiple strengths. For example, the classroom portion where
personnel discuss the activity to be performed reaches those who learn best by listening, and the role-playing activities reach those that learn best in a hands-on manner, and the observation of activities by a rating group reaches those that learn best by watching demonstrations. While it is a good training environment, it can be improved by creating a more believable training environment where the equipment appears in the context of the plant and where radiation exposure can be simulated.

Mockup training is an excellent method for training and reinforcing skills as the last chapter discussed; however, it does have shortcomings. A prime example of one of these shortcomings was demonstrated during a training session using the Performance Simulator at SSES. In the training scenario, a two member team was asked to tag out a number of valves in preparation for a maintenance activity. One team member would perform the task while the other double checked the work. The activity took place in a simulated radiation area with a clearly marked hot spot, which was pointed out to the team during the pre-job brief used to prepare them for the work. During the performance of the activity, the second team member, the peer checker, performed his entire task while standing directly in front of the hot spot. The team was wearing dosimetry, but it was not functional since the radiation was notional. The team member received no feedback that he was receiving significant radiation exposure, which might have caused him to change his position. He also did not appear to be able to suspend belief in the mockup even though it had the appropriate markings for radiation area boundaries and all of the proper signs were in place. The mockup training did not instill the proper attitudes through either a failure on the part of the learner to apply what he knew or on the part of the environment which did not allow the learner to achieve the proper mindset to apply
the knowledge. In this particular situation, virtual reality may have provided an improvement over the mockup training because the activity did not require tactile feedback (touch) and radiation exposure could be simulated and measured, giving feedback to the learner.

While virtual environments can easily be created to perform SCBA training or control room simulator training, the lack of tactile feedback in the virtual environment would be a serious shortcoming. The user’s vision was obscured in much of the mockup, forcing them to rely on their sense of touch to successfully complete the maze activity. In its current state, virtual reality technology probably would not be sufficient to teach the skills taught in the SCBA mockup. Similarly, operations personnel rely on the sense of touch to operate the plant, as Jim Beavers demonstrated. A virtual environment of a control room could be created with photo-realistic textures, but the current virtual reality technology cannot, in a minimally intrusive manner, recreate the different “feels” of buttons and switches that an operator uses. These are areas where adequate technology may eventually exist to use VR simulations, but, in its current form, virtual reality would not be sufficient for these tasks because of the importance of tactile feedback.

While the lack of tactile feedback in the virtual environment limits some of its applicability as a training environment for all tasks in the nuclear field, virtual reality and virtual mockups currently have sufficient capabilities to recreate plant-like environments with realistically modeled equipment, sound, and simulated radiation environments. The virtual environment must be tested before being deployed operationally, and this dissertation presents an experiment which evaluates the full-scale virtual environment technology in an application that is designed to mimic a possible real-world use.
Summary of Nuclear Training

Many rules and regulations and multiple organizations govern and direct training in the nuclear industry. While industry-wide standard training programs do not yet exist, the general subject information is fairly standard with each utility injecting its own flavor. The rules governing training do not specify how material is to be trained; rather they concentrate on what is trained and whether or not training is successful. As a result, training in the nuclear industry takes many different forms, although the Institute for Nuclear Power Operations (INPO) was formed to serve as an evaluator for the nuclear industry’s training programs.

As the four case studies indicate, different utilities handle training differently. Some rely on extensive use of hands-on training using mockups, while others rely on classroom-based training and computer-based training. The training decisions depend on the task that is being trained and the mindset of the training staff at the plant; however, best practices in training are often shared between utilities to improve training industry-wide through exchange programs, meetings, and peer reviews. According to Chockie et al. (1984), “83% of electricians, 71% of mechanical personnel, and 46% of instrumentation and control personnel expressed dissatisfaction with training efforts” (p. 306). While the information is dated, the results show that personnel want more from training. One training method that some research organizations are investigating is the use of virtual reality for various nuclear industry training applications. These efforts are described further in the next chapter.
Chapter 5

VR Applications in the Nuclear Industry

There has been some effort in the past to test visualization technologies in areas related to nuclear power, but the industry, as a whole, has been slow to adopt the technology, most likely due to the expense of the virtual reality (VR) display systems and difficulty quantifying benefits that are not subjective. While this is true, according to Lathan (2002, p. 403), “it is generally agreed that VE technology provides a new level of interaction and expands the application options that can be explored.” The authors continue by saying the goal in the development of virtual environments is “to find conditions in which training provides an adequate match (p. 405).” Hall, Stiles, and Horwitz (1998, p. 188) state, “…there is substantial promise in the combination of VR-based practice strategies with efficient instructional development. The central focus of future research should address the facilitation of instructional and practice strategies that lead to competent application of skills in the field.” The researchers found that trainees performing a procedure scored higher in immediate and delayed (1 week later) cases, and, in a second experiment, they also found that VR trainees scored higher in immediate and delayed tests in component identification. It should be noted that since that time technology has improved significantly. Kass and Ahlers (1998) evaluated two virtual environment technologies that could potentially be used for training: an image-based virtual environment and a model based virtual environment. They also provide a list of strengths and weaknesses for each technology determined during their search for a way to
train Navy personnel to perform material readiness inspections. According to Bliss, et. al., (1997), it is possible for people to learn procedures for moving from point to point in a virtual environment, basically establishing route knowledge. These statements about the application of VR technology raise an interesting question: Can virtual reality be applied to the nuclear field, as well?

Researchers at national laboratories and universities in the US, as well as organizations in Norway, Korea, Russia, the UK, Spain, and Japan, have investigated the use of VR for nuclear applications. Some recent examples of virtual reality research in the nuclear industry are highlighted in this chapter. Examples discussed include walkthroughs of planned facilities, various forms of training, outage planning, and decommissioning.

During the mid-90’s, a team at the Argonne National Laboratory looked at using virtual environments for nuclear power plant design. The researchers evaluated a number of products including InSight, Quick Time VR, and the CAVE™. They created virtual models of the Sodium Process Facility control room and the Sodium Carbonate equipment in 3-D Studio, a 3-D graphics design package. In addition to the 3-D Studio models, the team translated AutoCAD models of the Experimental Breeder Reactor II (EBR) for viewing in a CAVE™. This model and an animation of the EBR-II refueling sequence were introduced to two operators who remarked that the CAVE™ would be useful to explain how the systems function to new operators and engineers. The researchers cited the virtual environment’s ease of interpretation for non-technical reviewers as one of the strengths of the technology. They also remarked that the
CAVE™ is an “excellent tool for training in developing accurate user mental models” (Brown-VanHoozer, 1996, p. 316).

Stansfield (1996) of Sandia National Laboratory evaluated early immersive VR technology for architectural walkthroughs and training for three tasks. Using a head-mounted display and a BOOM3C viewer, users were able to walk around and view simulations of monitored retrievable storage (MRS) facilities, tour the waste isolation pilot project (WIPP) site for nuclear waste storage, and perform hot cell familiarization training. These early VR simulations were generally used for navigation of the environment and provided little interaction with the environment.

Engineers from British Nuclear Fuels, Ltd. (BNFL) designed a VR simulator to assist them with planning and execution of a pipe diversion task, which is discussed by Mort (1997). Because training the task on physical mockups was limited due to the high cost of materials and significant wear and tear on the equipment, they developed a VR system to provide additional training. Because the actual task takes place in a high radiation area, it is typically performed remotely using a snake manipulator and several work heads. The training system the engineers developed utilized desktop VR controlled by a joystick and the keyboard. As is the case with many VR applications from the mid-90s, the developers used Deneb Robotics Telegrip software to create the virtual environment. Models of the manipulator and workheads were designed in the Pro-Engineer software. The authors conclude that the primary advantages of the VR simulator are “the capability to explore ‘what if’ scenarios and finding faults developing on the equipment” (Mort, 1997, p. 1327). The VR trainer was successful in creating a sense of immersion for the operators, according to the authors.
Engineers at British Nuclear Fuels, Ltd. (BNFL) have evaluated the use of desktop VR for their Magnox reactors according to Smith (2000). The system was used as a planning tool and then a visualization tool for maintenance and welding applications. BNFL also evaluated the use of VR for control room design and operator training for a planned mixed oxide (MOX) fuel plant (Reed & Tunley, 1997). The authors note that the VR model of the control room seemingly reduced the number of design iterations required to lay out the control room.

Working with operators for the Russian-designed RBMK reactor, researchers at the Kurchatov Institute and the Institute for Energy Technology in Norway collaborated with personnel from the Leningrad nuclear power plant to develop a VR simulator to train operators of RBMK reactors in refueling operations (Bye, 2000). The simulator was created from a combination of Windows and LINUX workstations (Aliev, 2000). Control panels were simulated as soft panel displays that simulate physical gauges on a computer screen, while the refueling machine and reactor hall were simulated using VRML models. The researchers intended the simulator to develop basic knowledge and skills as well as to keep the skills of the operator fresh.

Researchers at Iowa State University investigated the creation virtual reality models of nuclear power plants, including display in a CAVE™ (Sharma, 2000). They created a model of a reactor coolant pump and displayed it in the C2 facility at Iowa State University. The researchers discussed many potential uses, but failed to fully describe any work beyond the use of the VR Juggler software and OpenFlight models, similar to work performed independently at Penn State using different software (Shaw, 2005).
Researchers at the University of Illinois have recently investigated methods of creating virtual reality simulations for nuclear applications (Uddin, 2003). Their research has focused on the creation of a virtual nuclear laboratory. The multi-station laboratory includes a simulation of a sub-critical graphite pile, a virtual control room, and a simple radiation shielding demonstration. The simulations, presented in a desktop environment with anaglyphic (red-green) stereo projection, were developed by programming the OpenGL commands (SGI, 2007) in the C++ programming language. While this method of creating simulations provides some flexibility, programming can be difficult and is typically not as robust as the use of commercially available tools. The applications have been tested in a CAVE™ at the University of Illinois (Karancevic, 2004).

For the past seven years, virtual mockups have been created for display in a CAVE™ at Penn State’s Applied Research Lab, including six nuclear-related virtual mockups. Room 12306 of the AP 600 nuclear power plant was the first virtual mockup created (Shaw, 2005). A full-scale mockup of the AP 1000 containment was created as well as a mockup of the AP1000 steam generator compartment. Three virtual mockups recreate existing physical mockups at two different power plants’ training facilities. A proof-of-concept mockup of the reactor cavity of the Pebble Bed Modular Reactor (PBMR) design was also translated. Much of this development was supported by a US Department of Energy (DOE) Nuclear Energy Research Initiative (NERI) grant, funded between 2001 and 2004 (Whisker, 2004).

Korea Hydro and Nuclear Power Co. and Ohio State University collaborated to develop desktop VR applications for e-training (Kang, 2002) and radiation dose management (Kang, 2003). More recently, the researchers have created a collaborative
virtual environment centered on a virtual nuclear power plant called Kodada-1. The virtual environment is designed to be shared over the Internet with multiple users sharing the same environment. The software includes a chat interface, which enables the users to virtually meet with distant colleagues. The virtual environment also includes a simulated radiation environment where the avatar’s (virtual human) radiation dose can be estimated and monitored. The system demonstrates a video game-like introduction to the nuclear power plant, which many can access (Kang, 2004).

Shin, Song, and Yi (2003) of KEPRI developed a VRML-based in-service inspection (ISI) planning and training tool. The researchers used 2-D drawings as the basis to reconstruct a 3-D model of the reactor vessel, reactor coolant pump, steam generator, pressurizer, and the piping that connect them using the 3D Studio Max modeling software. The graphical information was linked to a database where the ISI results were stored. The system was used to train plant personnel to increase the efficiency of ISI. The researchers report that using the VRML ISI training system inspection routes were standardized and accidental omission of inspection points was decreased. Along the same lines, British Energy developed a VR system for training engineers to perform ISI, as well as assembly and disassembly of reactor components (Molland, 2001).

A few utilities have adopted some form of VR technology. Examples include San Onofre Nuclear Generating Station’s (SONGS) use of product lifecycle management tools from Dassault to simulate complex operations such as underwater construction and steam generator replacement in desktop virtual reality (Stephens, 2006). According to David Lisbinski (2005), the radiation protection department at Susquehanna Steam
Electric Station has created Quicktime VR models (Apple, 2007) of many areas of their plant for familiarization training. The models enable a user to view 360-degree photographs of plant equipment as seen from a fixed viewpoint.

Researchers have evaluated VR technology for decontamination and decommissioning activities. Wuller, *et al.* (1995) and Pot, Thibault, and Levesque (1997) studied VR as a means of simplifying decommissioning when it looked as if the industry was going to move in that direction. Wuller’s group used close-range photogrammetry supplemented with modeling software to create accurate models of an area of the Fernald plant in Ohio, a Babcock and Wilcox high enriched uranium fuel facility, and a number of sites at Oak Ridge National Lab. Simulations were created using the IGRIP software, which was a popular VR suite at that time. Pot’s group used LIDAR to survey the space and then reconstructed CAD primitives using the data from the point cloud created by the LIDAR measurements. This enabled them to create accurate as-built models of the physical site. The models created were applied to the dismantling of the Brennitis plant.

Engineers from Iberdrola in Spain have developed four desktop virtual reality applications showing many applications of VR for nuclear power plants (Felipe, 2003). CIPRES, Interactive Calculations of Radiological Protection in a Simulation Environment, dynamically calculates the dose to “workers” in a desktop virtual reality simulation. CIPRES has been applied to dose management of BWR refueling activities at the Cofrentes Nuclear Power Plant (Rodenas, 2004). The program shows a VR simulation of operations in a desktop virtual reality system, calculates the dose to the workers during each process simulated, and defines each activity and operator action during the simulation. “The aim of the application is to become a training tool for
operators involved in refueling operations, so that both operation time and received dose could be minimized” (Felipe, 2003, p. 2).

A second software package, TILOS (Turbine Planification for the Simulation of Turbine Dismantle), can simulate the procedures for dismantling the turbine for maintenance or changeout. The program can be used to investigate laydown spaces and component arrangements for maintenance. The software was used to study the turbine maintenance scenarios for the Cofrentes plant. The program output a Microsoft Project file with each of the operations performed in the dismantling procedure (Felipe, 2003).

A third package, ACEWO, is a first person demonstration of the access control procedures for a nuclear power plant. The software, used as a training tool, is comprised of four modules: access to controlled areas, exit from controlled areas, ALARA, and learning about protective clothing. Each module can operate in 3 modes: an automated step-by-step mode, a stand-alone mode that prompts the user for action, and an evaluation mode that ensures the user performs operations in the correct order (Felipe, 2003).

The final package, SICOMORO, is designed to optimize the design of control rooms. The program was designed to study the man-machine interface between the operator and the control room. The software was used to assist employees to select and lay out new furniture for the Cofrentes nuclear power plant (Felipe, 2003).

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

One of the more significant efforts in the area of VR related to nuclear power has been that of the Institute for Energy Technology (IFE) in Halden, Norway. Four of the studies they performed are presented here. In one experiment, Sebok (2002) and colleagues from the IFE developed a desktop virtual reality training system to evaluate spatial familiarization methods. The participants were trained using maps, guided VR and unguided VR. In the guided VR method, participants were instructed to follow a 30 meter path connecting six points of interest. In the unguided VR method, participants were free to explore paths between the points of interest. In addition to transfer of route knowledge, the system was designed to evaluate radiation awareness of participants. Once the training in the VR was performed, participants entered the actual Reactor Hall and performed the measurements on the points of interest. After the experiments were completed, participants were surveyed and observed to determine radiation awareness,
subjective transfer of training, subjective impression of interaction quality, and their opinion of the presence and usability of the system. Objective measures included time required to complete the task, number of measure points correctly recognized, route length, and radiation dose received.

The results of the study showed that participants were better able to locate the measurement locations after training using the two VR methods than were those who trained using the 2-D map. Additionally, the non-guided VR group outperformed the guided VR group and the map group. This result suggested that the subjects who were engaged in active learning were better able to transfer what they had learned in the VR trainer to the real-world situation (Nystad, Droivoldsmo, & Sebok, 2002). The researchers note that “the training program must require active learning, which engages the learner, to fully realize the potential benefits of the technology” (Nystad & Sebok, 2002, p. 8-21).

The second series of experiments evaluated different technology types for training (Sebok & Nystad, 2004). The researchers trained subjects using multiple technology types: desktop monoscopic, desktop stereoscopic, large-screen monoscopic, large-screen stereoscopic, and head-mounted display. The technologies were varied depending on the task being evaluated – procedural knowledge, configuration knowledge, and assembly knowledge. Procedural knowledge was tested by teaching personnel to perform a step-by-step procedure in a VR model of the Halden reactor hall and then testing their knowledge during a walkthrough of the actual reactor hall. Configuration knowledge was evaluated by measuring the subjects’ radiation awareness during the procedural experiment. Assembly knowledge was tested by asking students to study a complex
assembly in VR and then draw and label the parts. The researchers found that technology type did not matter for the training of procedural, configuration, or assembly knowledge; however, they found that retention and transfer of knowledge was higher in stereoscopic environments, more so in large-screen stereoscopic environments (Sebok & Nystad, 2004). This result suggests that a fully immersive system, such as a CAVE™, would be a good training system for spatial concepts such as radiation sensitivity because of high knowledge retention and effective transfer of knowledge.

In a third series of experiments at Halden, the researchers compared two different methods of displaying radiation field data on four different display systems (Nystad and Sebok, 2005). Radiation field data was shown in a window separate from the VR walkthrough using two methods. The radiation was shown by either a 2-D overlay of colors or by a 3-D topographical feature using color and elevation. The four display systems tested were desktop monoscopic, desktop stereoscopic, large screen stereoscopic, and HMD. The results of the experiments showed that the maps were each valuable for different purposes; the flat map was better for general understanding of the radiation field in a large area, and the topographical map was better for showing peaks and hot spots.

Most recently, the research team discussed using VR to train field personnel (Nystad & Strand, 2006). They tested the personnel using a front projected single screen display (4.93m x 1.87m) and a rear-projected single screen display (3.66m x 1.42m). The researchers constructed VR models of rooms within a nuclear power plant. These VR models were linked to a simulator model which enabled users to click on buttons to trigger a menu and perform various operations in the plant. Data from the experiments was collected using surveys and interviews. The results of the experiment showed that
field operators were able to successfully perform simulated tasks in the virtual environment.

A joint project between the Japanese Nuclear Cycle Institute and researchers at the IFE, developed a system called DEXUS, designed to assist engineers with planning decommissioning activities for the Fugen nuclear power station. A desktop application utilizing 3-D CAD data was merged with a database containing additional data such as weight, material, activity, contamination, and radiation dose rate. The application could be used for visualizing equipment on the desktop, scheduling dismantling activities, visualizing dismantling movements, and evaluating masses of components (Iguchi, 2004).

Additionally, the researchers developed a capability to optimize the dismantling plan with a package called COSMARD. The package enables the engineer to consider work breakdown structure, radiation dose, available manpower, and schedule when planning activities. It also measures the waste mass for disposal purposes. Models created in COSMARD can be re-used for multiple decommissioning activities if common components are used (Iguchi, 2004).

The most significant tool developed under this program is perhaps the VRdose program. The program allows engineers to plan and simulate human movement to evaluate workload and radiation exposure. The software simulates the movement of manikins, virtual humans, around a virtual space. In this case, the engineers are moving the manikins around a 3-D CAD representation of the Fugen Reactor. Scenarios, including interaction between manikins (avatars), can be recorded and played back for discussion and optimization. The software includes a navigation area that enables the user
to navigate through a VRML model of the space while visualizing the radiation environment. A second area enables users to record, edit, and store work routes, animated work sequences, and operations, including the use of virtual tools. The third function enables the user to evaluate the radiation exposure experienced by each worker during the scenarios developed in the scenario recording area. This can be used to optimize activities to reduce radiation exposure. Finally, the worker data area contains a database that stores information about the real-world task, which may include duration and previously experienced radiation exposures. A one-screen stereoscopic display can be used in conjunction with the VRdose program to view the output in 3-D (Iguchi, 2004).

Based on the many different applications where desktop and some forms of immersive VR were applied to nuclear issues for design, operation, and decommissioning, one can surmise that similar performance is possible using immersive VR training for nuclear applications similar to the way that physical mockups are used today. There has been a small amount of VR-based nuclear training. Two organizations that have performed research in this area are featured below.

Hanes and Naser (2004) performed work for the Electric Power Research Institute (EPRI), which discussed a number of VR applications, as well as areas where the various forms of VR may be applied in the nuclear industry. One particular application highlighted was a VR training system developed by KEPRI in Korea. In discussing this application, they note,

According to a spokesperson for Eversoft Co., Ltd… a 90% cost reduction is expected in training costs compared with alternative simulation training methods. The basis for the reduction includes quicker training roll out,
reduced classroom time, increased retention, and improved self-study capabilities. (Hanes, 2004, p. 8)

In the full EPRI report, Naser (2004) lists a number of areas where VR may have applications to the nuclear power industry, specifically operations, maintenance, training, and engineering.

Iguchi (2004) and colleagues from the Japanese Fuel Cycle Institute and the Institute for Energy Technology developed a system for planning the decommissioning of nuclear power plants. He suggests, “The possibility of training for the work tasks in advance, along with better planning and briefing should lead to an optimization of the radiation dose and minimization of workload and consequently result in a cost reduction (p. 373).” The research performed by Iguchi and his colleagues are detailed further in the following section.

In addition to the VR Dose application presented earlier, a number of VR applications have been developed to simulate radiation environments. Knight, Dalton, and Tulenko (1997) used Deneb Robotics IGRIP software to plan work in the radioactive waste storage tanks at the Hanford site. The desktop VR simulation included a Monte Carlo-based radiation model to estimate dose to the robot and operations personnel. Rodenas et al. (2004) developed a VR application to train personnel for BWR refueling operations. The application included 2-D and 3-D dose maps, and it estimated and tracked the radiation exposure using a square mesh to estimate the dose at multiple work locations. Doses were estimated using the MCNP4-C Monte Carlo code. Neither application reported quantitative dose reductions resulting from their use, but the authors do laud the technology as being applicable for dose reductions.
Summary

Over the past ten years, many organizations and laboratories have studied the use of virtual reality for various applications relating to nuclear power. Applications ranging from simple walkthroughs of nuclear facilities and plant access training to experiments involving radiation awareness have been created. A number of well planned and documented experiments have been performed, but many of the other applications appear to be programs implemented in research organizations, and it is unclear whether they were applied in the field.

The majority of applications have been developed for desktop environments, although a few have ventured into the realm of immersive VR via CAVEs or HMDs. This is most likely due to the expense of hardware and the level of effort involved in the first-time development of applications. It may also be because of the view by many that VR is still a developmental technology. Also, as shown in this chapter, there have not been many groups working to advance the technology in the nuclear industry, but other industries have embraced the technology and have pushed its development. The applications listed in this chapter show applicability to the entire lifecycle of the plant, ranging from designing a control room to operator training and maintenance to decommissioning.

As the applications discussed in Chapter 4 demonstrated, physical mockups, both full-scale and reduced scale, have been used to successfully reduce worker dose on outages where they have been applied, particularly for steam generator replacement. Other applications have used physical mockups in training basic work practices such as
STAR (Stop, Think, Act, Review) and peer checking. Immersive virtual reality should be able to create similar training environments, but with the added element of simulated radiation dose calculations. This is expected to improve work planning and task training, since the physical mockups do not offer this capability and dose reduction is a principal concern of utility management. As Lathan (2002, p. 405) states, “virtual environments provide a means to fulfill the objective of training in the objective environment without really being there.”

Virtual reality technology has advanced significantly since the early work was performed at the national labs. Virtual reality, more specifically immersive virtual reality, has become significantly more usable recently with the advent of wireless interaction devices, accurate head tracking, and more ubiquitous content. Visually accurate virtual environments can now be created and used by personnel beyond those developing the applications. The virtual environments are also capable of displaying additional simulation data, such as ionizing radiation, with the model geometry to create an even more believable environment. An experiment, described in the next chapter, has been created to test this supposition.
Chapter 6
Experimental Methodology and Pilot Study

Given that many factors influence nuclear training – safety, regulations, financial considerations, logistics, the teaching of complex concepts – and the training potential offered by virtual reality simulations, each discussed in previous chapters, an experiment has been designed to assess the application of Immersive VR for Radiation Awareness Training. Radiation awareness is an important component of Radiation Worker Training at Nuclear Power Plants.

Radiation worker training is intended to train personnel to reduce and maintain radiation exposures to be As Low As Reasonably Achievable (ALARA). Currently these training programs offer few methodological options to train and assess personnel in the concept of radiation awareness. The most commonly used method is computer-based instruction. In some cases the computer based training is supplemented by hands-on training activities that simulate radiation exposure using a special survey meter. Immersive virtual reality may provide a means of performing this training more effectively, taking advantage of its ability to accurately present plant equipment and to track radiation fields and associated worker exposures, which the teams at Halden (Sebok, 2002) and Iberdrola (Felipe, 2003) demonstrated was possible using desktop virtual reality.

Based on information in the literature and discussions with nuclear utility training personnel, most of the radiation awareness training performed by utilities today has
transitioned to computer-based training. Taking advantage of some of the unique characteristics of more immersive forms of virtual reality, training can be enhanced by conducting exercises in a manner more akin to what personnel will encounter in the plant environment. The resulting training environment is similar to the actual work environment both physically and psychologically, which is helpful to knowledge transfer and retention. The virtual environment also allows for authentic assessments to be performed and for simulated radiation exposure to be monitored, where scenarios can be practiced multiple times with the eventual goal of error-free performance, and where feedback can be given instantaneously.

The experiments discussed in this and the following chapter were designed to compare training methods that are similar to those currently in use in the nuclear industry (computer-based reading of manuals and PowerPoint presentations) with training methods that are activity based.

**Hypothesis**

The research discussed in this dissertation aims to show that radiation awareness is higher in workers that have received activity-based training in a full-scale virtual mockup than those trained using only traditional methods such as computer-based training. Improved awareness will be assessed by measurement of radiation exposures during defined tasks; the magnitude of errors in source location and quantification; the degree of radiation hazard recognition; and completion times when performing tasks in a virtual power plant environment. One would expect radiation awareness to be higher for
those receiving some variety of hands-on training because it 1) offers firsthand experience and 2) because radiation is highly spatially dependent which can be better visualized in a 3-D environment. High radiation awareness would be exhibited as low radiation exposure, fast completion times, successful completion of assigned tasks, and performance of thorough 3-dimensional surveys. The null hypothesis contends that radiation awareness is unaffected or negatively affected by the virtual reality training method.

**Method**

To determine the effects of the training, a combination of qualitative and quantitative measures were employed. Surveys, tests, and an assessment activity were designed to collect data to prove the hypothesis. Figure 18 shows the flow of the experiment. A pre-experiment survey was designed to collect basic information about the subjects. A pre-test then measured their knowledge of radiation prior to training. Computer-based training provided basic knowledge about radiation, followed by the initial orientation, training the subjects to operate the virtual environment. Next, some of the subjects received supplemental training, either hands-on with a simulated radiation meter or activity-based training in the virtual environment. Once all of the training had been completed, all subjects regardless of training method completed activities to assess their learning, which included a practicum in the virtual power plant and post-test to assess learning. Finally subjects completed a second survey to gauge their attitudes and
feelings about the training they received. Data was collected at each of these steps to allow the researcher to assess the subject’s radiation awareness.

Two experiments were performed to test the radiation awareness improvement of subjects trained using multiple methods. The first of these experiments, a pilot study, is discussed in this chapter, while the second, a final assessment, is discussed in the next chapter.

The pilot study tested the improvement in radiation awareness after three methods of training. Following the procedure discussed above, one group completed only the computer based training and served as the control group for the exercise. The next group completed the CBT and then performed supplemental hands-on activities with a simulated meter. The third group was trained using computer-based instruction supplemented with activities in an immersive virtual environment. The segments of the experiment are described in the sections that follow.

In the sections that follow, discussions of the surveys, tests, and assessment activity that subjects completed during each experiment trial will be presented.
Pre-Experiment Survey

The first survey collected basic demographic information about each subject such as age, job information, and years of experience. This information assisted the researcher in gauging the overall experience-level of the subject. A screenshot of the questions is shown in Figure 19.

![Screenshot of Pre-experiment Survey on ANGEL](image)

Figure 19: Screenshot of Pre-experiment Survey on ANGEL

The subjects were asked if they had ever had unescorted access to a nuclear power plant or Penn State’s Breazeale Reactor, since a positive response would mean the material in the computer-based training should be familiar. It was assumed that subjects selected from nuclear engineering had received some level of nuclear general employee training (NGET), radiation worker training (RWT), or introductory radiation awareness training during internships or their education. The subjects from nuclear engineering
were asked to report when their last training or re-training occurred to determine the freshness of the information they had learned.

Next, subjects were asked to report the learning method they felt worked best for them, choosing from reading books or procedures, watching demonstrations, performing hands-on activities, receiving instruction in a classroom lecture environment, or completing computer-based or web-based training. This question was intended to allow the subjects to self-identify their perceived strengths. The need for this information is based on the work of Gardner (1983), who proposed that people have multiple intelligences that explained the subjects’ preferences for different learning methods. For example, if the subjects learn best in situations that can be trained using hands-on methods, the virtual reality training, which contains strong spatial, visual, and hands-on components, would be expected to show higher radiation awareness than the CBT-only method. Regardless of their choice, all subjects participated in the experiment. Next, subjects were asked if they had experienced virtual reality visualization, either desktop or immersive, prior to this experiment. Finally, the subjects were asked whether they considered themselves to be technologically savvy and computer literate, in an attempt to expose potential biases for or against the visualization technology or new technologies in general.

**Pretest**

The pretest established a baseline of each subject’s radiation awareness. It was comprised of six questions, a combination of basic concepts and simple problems
designed to determine whether or not the subject possessed a basic knowledge of the components of ALARA and the relationship between dose rate and dose. The final question on each survey asked the subject to choose a visual representation of the path with the lowest potential radiation exposure from three choices. The question was designed to assess the subject’s understanding of the ALARA concept applied to navigation through a radiation area. Sufficient information was not provided such as walking speed or exact distance, so the subject had to use their judgment to answer the question. The quiz and the survey served to provide some basic information about the subject’s level of radiation awareness prior to the experiments.

**Maze Training**

To allow the subjects to become acclimated to the virtual reality system, they first completed an orientation activity. The subjects were introduced to the controls of the CAVETM virtual reality display system, navigation in the CAVE™, and the use of the virtual survey meter and dose modeling program. They were trained to navigate by traversing a full-scale mockup of a maze shown in Figure 20, which required approximately four minutes to navigate from start to finish if the subject did not get turned around. Subjects began at the labeled start position and ended at the room labeled finish. Colored barrels and other markers were placed throughout the maze to provide landmarks so the subjects could establish route knowledge as they proceeded through the maze. The optimal path has been drawn on the figure.
By training all subjects to operate the CAVE’s controls during the initial orientation phase, it was intended that they would be able to concentrate on only the task at hand for subsequent activities and not be distracted by learning the CAVE technology. This potential distraction had previously been cited as a potential drawback of virtual reality training (Wickens, 1992). Upon completion of the orientation maze, subjects were
asked about their comfort level with the navigation and operation of the controls in the virtual environment. Subjects were allowed to repeat the navigation through the maze as many times as necessary until they were comfortable with the navigation. No subjects, however, took advantage of this offer. This author’s experience training hundreds of users to operate the virtual environment suggests that most subjects, including those who are not typically technology users, quickly learned to operate the navigation controls, becoming comfortable with their function in a short time, typically minutes.

The radiation awareness training for this experiment was delivered using three methods, as shown in Figure 21. The pool of participants was split evenly so that similar numbers received training using each method. Participants in all groups completed computer-based training using the radiation awareness manual and the PowerPoint presentation, similar to the training that workers at nuclear power plants perform. One group received no further training (CBT group), one group received supplemental training with the Teletrix simulated survey meter (Teletrix group), and the third group received supplemental training in the virtual environment (CAVE group). The three methods are described further below.

![Experiment flow for Pilot Experiment Groups](image-url)

Figure 21: Experiment flow for Pilot Experiment Groups
Computer Based Training Only

The first of the three groups received only the computer-based training. The CBT group’s activity was designed to closely mimic the current initial radiation awareness training received by personnel in the nuclear industry. The performance of the CBT group was intended to provide a baseline from which the performance improvement, if any, for the hands-on and virtual reality training groups could be measured. This group received no further training, so once their navigation training was completed, the group proceeded to the assessment phase of the experiment.

Hands-on Training with Teletrix Meter

The second group completed the computer-based training program just as the first group had, but the second group’s training was supplemented with a hands-on training activity using a Teletrix radiation simulation meter. Using the simulated meter, subjects measured the radiation level as it dropped off from a source. Since the Teletrix system does not directly simulate radiation - it depends on input from an instructor - the correct readings were obtained from the virtual dose model for the appropriate distances from the source. Tape marks placed on the floor at one-meter intervals guided the subjects as they performed their measurements over a stretch of six meters. The subjects recorded the radiation reading at each location on a worksheet, a copy of which appears in Appendix B. Once the measurements were complete, they summarized their observations on the worksheet. For this activity, the subjects were expected to note the decrease in the
radiation level as they moved away from the source, initially dropping quickly and then more slowly.

Next, subjects learned the importance of diligence and expediency in the radiation environment by performing an activity to show the effects of the time component of ALARA. To do this, subjects took a reading of the radiation level at a distance of approximately two meters from a source. Next, they were timed as they read two passages after taking a reading of the radiation level. The first passage, Robert Frost’s poem “The Road Not Taken,” took most subjects approximately one minute to read. The second passage, the second paragraph of the U.S. Declaration of Independence, required approximately two minutes to read. Using their radiation reading and the elapsed time they had spent reading, the subjects calculated the radiation exposure they had received. Unfortunately, at the time the experiments were conducted, the Teletrix system could not yet model the readout of a personal alarming dosimeter (PAD), so those results had to be simulated by integrating the readings of the survey meter over a period of time. The Teletrix group used a dose calculator to convert their radiation reading and time into dose. Finally, the subjects were asked to summarize their understanding of the relationship between time and dose based on their observations. Subjects were expected to discuss the linear relationship between time and dose.

**VR Training**

The last group completed the computer-based training supplemented by an activity in the virtual environment. A simple model, shown in Figure 22, was created to
provide activity-based training. A strong source was placed in the model and marked with a green triangle. Subjects measured the radiation level at each of the red balls to help them to see how the radiation field decreases with distance. The balls were spaced 1-meter apart, similar to the activity performed with the Teletrix meter. The subjects recorded the measurements at each location on a worksheet. Once all of the measurements had been taken, the subjects were asked to summarize their findings. They were expected to notice the decrease in the radiation level as they moved away from the source. Astute subjects would quickly observe the inverse-square relationship between radiation level and distance, meaning they would see that the radiation level was proportional to one over the distance from the source squared.

Figure 22: Dose Profile Demonstration

A second activity, similar to the second activity performed with the Teletrix, demonstrated the effect of minimizing the time spent in a radiation environment.
Participants were asked to take a radiation reading then read a passage, Robert Frost’s “The Road Not Taken,” which took approximately 60 seconds to read. They were asked to record the dose received during this activity. The sequence was repeated using a passage taking approximately 120 seconds to read, the second paragraph of the U.S. Declaration of Independence. The virtual reality version of the activity is shown in Figure 23. Again, the participants were asked to record the dose received. They were asked to compare the two numbers to determine the effect of minimizing time on radiation exposure.

![Figure 23: Dose Reduction via Minimizing Exposure Time Activity](image)

After the training activities were completed, the Teletrix group and the CAVE group moved on to complete the assessment activity in the virtual environment.
Assessment Activity

Once they had received the designated training, the subjects’ levels of radiation awareness were evaluated using a practical exercise, a post-training quiz, and a survey. The practical exercise, which took place in the virtual environment, was a synthesis of the activities the subjects had completed during training including navigation through the virtual environment, use of a survey meter, and general understanding of radiation dose reduction techniques. Subjects were given ten minutes to study a “work package,” a copy of which can be found in Appendix B, that contained a description of their tasks, a map of the plant, and a dose map. The process was designed to be similar to a pre-job brief, where workers typically perform a walkthrough of their task, review procedures, and become familiar with the equipment.

When their study of the activity was completed, the subjects navigated through a virtual power plant environment, stopping to perform simulated activities along the way. The first activity asked the subject to locate the highest radiation reading in a room that stored barrels. The second activity tasked the subjects with selecting between two locations where a worker could replace a filter on a piece of equipment. The third activity had the subject select between two paths through a radiation area. Finally, for the fourth activity, the subjects had to locate and mark a hot spot. Once the tasks were completed, the subjects exited the virtual plant by following the safest route.

Radiation sources were placed throughout the plant, and the subjects were expected to use the virtual survey meter to complete the measurement and marking tasks, while managing their radiation exposure. After they completed the exercise, the dose
model was stopped and results were recorded. A copy of the scenario description and the handouts appears in Appendix B.

**Post-experiment Quiz and Survey**

After all of the activities had been accomplished, the subject completed a short post-test, shown in Appendix B, to evaluate the transfer of the training. The post-experiment quiz followed the same form as the pre-test, but the questions were of increased difficulty. The six question quiz asked the meaning of the acronym ALARA and the three components of ALARA, and it also asked the subjects to complete a number of calculations. The difference in pre- and post-test scores was used to measure how much the subjects had learned from the training.

Finally, a survey was used to capture additional information on attitudes of the subjects, to assist with the analysis of the results. The survey inquired about the subject’s level of satisfaction with the computer-based training and the activity-based training. Their feelings on the ease of learning the virtual environment were solicited. Finally, the subjects were asked to rate their performance on the assessment activity in the virtual power plant. A copy of the post-experiment survey appears in Appendix B.

**Data**

Data collected consisted of survey results, pre-test results, post-test results, assessment activity performance, and general observations. The pre-experiment survey
was designed to provide background information on the test subject. Responses to the survey were used to help explain subjects’ performances in the experiment. Pre-test and post-test results consisted of raw scores out of a possible six correct answers on each test. The questions were intended to test basic knowledge, calculation ability, and spatial understanding. Data collected during the activity assessment included radiation dose received, completion time, radiation measurement in area 1, work location selection in area 2, path selection in area 3 and 4, and location of the hot spot in area 5. In addition to these quantitative measures, qualitative observations were made while the subject completed the activities.

Assessment of Radiation Awareness

To assess their radiation awareness, each subject who completed the pilot experiment received a radiation awareness score based on their performance on the various elements of the experiment trial including post test score and performance on the assessment activity. Scores between zero and one were assigned to each element of the trial.

Seven elements were combined to generate a radiation awareness score. The performance on the post experiment quiz was the first element, and the quiz score was based on the percentage of questions answered correctly. Proper location and measurement of the source in the first room of the assessment activity was the next element. A score was assigned based on the recorded strength of the source as reported
by the subject. If the noted strength was greater than 20 mR/hr, the subject was given a 100% (1.0) on that task. Readings lower than 20 mR/hr were assigned a score of zero. Next, the choice of work location was scored. If the work location with the lowest radiation reading was selected, the subject received a score of 1.0. Conversely, if the work location was not correctly selected, the subject received no points. Next, the choice of path was scored. Again, correct selection of the path resulted in a score of 1.0, and an incorrect selection resulted in a score of zero. Accurate location of the radiation source in the next activity was designated by an error less than 1 meter, which resulted in a score of 1.0. Because the magnitude of the “hot spot” used in this portion was only slightly above the surrounding background radiation readings, partial credit was given based on the following scale: Error of one to two meters resulted in a score of 0.5 since the source could still be located from that distance, and error of greater than two meters resulted in a score of zero.

The total dose received during the plant walkthrough activity was also scored. In an attempt to measure the efficiency with which the subjects completed the assessment activity, the average dose received per unit time was calculated by dividing the final dose reading by the total time spent in the virtual plant. The score for each subject was calculated relative to the best score achieved in the exercise. The score for each participant was divided by the minimum observed dose per unit time, which resulted in a score of 1.0 for the most efficient run. The subject’s completion time received a similar treatment. The minimum observed completion time was divided by each subject’s completion time, which resulted in a score of 1.0 for the fastest run.
All of the components were summed and then divided by seven to calculate the final radiation awareness score. This final score was used to quantify overall performance and understanding of the concept of radiation awareness. The score was designed to combine the traditional measures of awareness, such as the quiz, with the activities in the virtual power plant to yield a more complete assessment of the subject’s understanding.

**Instruments Used**

The hardware and software used in this experiment included computer based training programs, an online system for distributing and managing information, and media for the experiment. The media included a simulated survey meter and a high-end virtual reality display. The materials are described in this section.

**Computer Based Training**

The computer-based training module consisted of two files. The first was based on the First Energy Nuclear Operating Company (FENOC) radiation worker training (RWT) manual (FENOC, 2005), a PDF document supplied by James Byrne at Three Mile Island. The second file was based on a PowerPoint presentation available on the Internet from Georgia Tech’s Office of Radiation Protection that served as the multimedia portion of the computer based training (Georgia Tech University Office of Radiation Protection 2006). These files were adapted for use in the experiment and were made available to the
participants via a webpage. These documents were selected based on their content and availability. Based on the author’s experience at other power plants, the documents were representative of the materials typically used in nuclear utility training.

**ANGEL Content Management and Delivery System**

ANGEL, Penn State’s Course Management System, enabled the researcher to create a group for the management, distribution, and collection of information. For this experiment, ANGEL was used to store multiple files to be viewed by the participants. The system recorded information about the users’ performances on the pre-test and post-test and the two surveys related to the experiment. The number of times each file was viewed by the users is automatically recorded by the system, assisting the experimenter with recording of data. The system also assisted the researcher with the creation and administration of surveys and quizzes. ANGEL recorded the survey data and quiz responses. The item analysis tool enabled the researcher to see a breakdown of all responses on the surveys and quizzes. This feature simplified the collection and analysis of the data. The ANGEL system improved the delivery of the CBT and the administration of quizzes and surveys. Figure 24 shows the content page in the ANGEL system.
The Teletrix simulated radiation meter, a Ludlum model 2241 with Probe Pack attachment, was used as a hands-on training aid. The Teletrix system simulated the response of a survey meter in a radiation environment. The meter’s response was driven by a remote control that communicated with the meter over a radio frequency. When the
instructor turned the dial on the remote control, the radiation reading displayed on the meter changed accordingly. Using the probe pack attachment, a fully-functional, off-the-shelf meter was used since the probe pack simulated the pulses that the meter detects in a radiation field. Participants used the simulated meter, shown in Figure 25, to demonstrate the effects of distance and time on their radiation exposure.
CAVE Immersive VR Display

The virtual reality training environments were presented in a high-end, fully-immersive visualization environment, a 5-surface CAVE™ display, shown in Figure 26. The CAVE™ displayed computer-generated images on four walls and a floor. Each wall measured 10’x8’ with a resolution of 1312 x 1050 pixels. The floor was 10’x10’ and had a resolution of 1050 x 1050 pixels. The CAVE™ projected images in stereoscopic 3-D at 96 frames per second. Active shutter stereo glasses created the 3-D visual effect by separating the left eye and right eye images. The images were generated by a cluster of five Dell 490 PCs with nVidia QUADRO FX 5500 graphics cards. The CAVE™ was used to display virtual mockups, full-scale representations of CAD models that enabled users to navigate and interact with building designs, ship designs, and others before they were built.

Figure 26: Penn State ARL’s CAVE™ Display
Coupled with the CAVE™ display environment was an Intersense IS-900 wireless tracking system, which included a Minitrax wand and a head tracker. The Minitrax wand enabled the user to navigate the virtual world. On the wand were six programmable buttons that were configured to perform multiple actions, which enabled the user to interact with the virtual mockup. The wand showed the extent of the user’s reach in the virtual environment by displaying a virtual representation of a hand. The head tracker continuously updated the display based on the point of view of the CAVE™ user. As the user moved his or her head, the display changed to show the view that would be seen from that position. The tracking system enabled the user to interact with the virtual environment more naturally than one could on a desktop computer. This interaction was one of the key features of immersive virtual reality.

The simulations developed for Penn State ARL’s CAVE™ environment were created using commercial-off-the-shelf software, coupled with additional functionality built by the staff of Penn State ARL’s SEA Lab. Multigen-Paradigm’s Vega and Vega Prime (Multigen-Paradigm, 2006) software packages provided basic functionality and interface tools, while Explorer and vpExplorer provided additional functions to enhance the utility of the two simulation packages, respectively. Vega and Vega Prime were originally developed to support the U.S. Military’s simulation community. Explorer and vpExplorer were developed to tap into the Vega and Vega Prime application programming interfaces, respectively, to enable the user to naturally navigate and interact with the virtual environment.
Full-scale Virtual Mockups

Three virtual mockups were assembled for the pilot experiment. A maze, which typically required three to four minutes to navigate, was constructed to train subjects to navigate in the CAVE™. Throughout the maze colored barrels and hazards were placed to assist the user with creating mental waypoints. Second, a long hallway model was constructed for use with the time and distance virtual training activities. In this mockup, a strong radiation source was placed at one end of the hallway and markers denoting measurement locations were placed along the length of the hall. Finally, a CAD model of the auxiliary building of the AP1000 was stripped of equipment and repopulated with generic equipment models to support the tasks of assessment scenario. Images of these mockups appear in the appropriate sections describing the pilot experiment.

Virtual Radiation Dose Model

A radiation dose simulation model was developed to perform real-time dose estimations in a virtual radiation environment. Dose profiles were overlaid on the virtual mockups, enabling a user to interrogate the radiation field with a virtual survey meter, similar to the one shown in Figure 27. On the walls of the CAVE™, the user could see the radiation levels measured in milli-Roentgen per hour (mR/hr) and the cumulative dose in millirem (mrem). As the user moved the Minitrax wand over the virtual radiation source, the dose rate was recalculated instantaneously and the new information was displayed when the dose modeling program was activated. The model represented the Time and Distance components of ALARA, but currently it cannot represent shielding...
due to the model limitations of the real-time calculation. Additional information about the radiation dose modeling appears in Appendix A.

Figure 27: Simulated Radiation Meter in Use

The ANGEL system, the Teletrix meter, and the CAVE display supported multiple portions of the experiment. ANGEL was used to deliver the computer-based training and to record and compile results for the surveys and tests. The Teletrix meter provided a hands-on training aid, and the CAVE display was used for virtual reality training and for the assessment activity.
Variables

To measure a subject’s radiation awareness, a number of variables were used. The dependent variables for the experiment included radiation dose, completion time, successful location of sources, measurement error, number of tasks completed successfully, and pretest and posttest scores. These variables were measured directly during the experiment. The independent variable was the subject’s training method. In this case, Computer Based Training (CBT), CBT with simulated radiation meter, and CBT with virtual reality training were considered.

The variables of interest selected for the experiment were chosen for several reasons. The radiation dose received during the activity should be indicative of the subject’s radiation awareness – a subject who receives more radiation exposure is expected to have lower radiation awareness, while a subject who receives less radiation exposure is expected to have higher radiation awareness. Working in the radiation environment, obviously all subjects will receive some radiation dose, but they must make an attempt to minimize their exposure. Radiation exposure is probably the most direct measure of the subject’s radiation awareness, although it fails to paint a complete picture of why or how the subject received this radiation dose. For this reason, other measures have been developed to provide additional information about the subject’s radiation awareness.

One of the three factors contributing to ALARA, the completion time, is also an important factor to be considered. A subject who takes less time to perform the tasks can be either sloppy or deliberate, so this information must be evaluated by considering other
factors such as overall radiation dose received. The completion time measure exposes one of the more important tradeoffs one must consider when evaluating radiation awareness – the balance between thoroughness and expediency.

Performance on the source location and measurement tasks were measures of the thoroughness of the radiation survey performed by the subject – correct location and magnitude indicate that a thorough survey was performed. Locating a source while managing radiation exposure required the subject to balance thoroughness with care so that they did not receive large radiation exposure as they located the source. When combined with radiation exposure received and completion time, the efficiency of the subject’s survey was gauged.

The subject’s understanding was tested more deeply on two tasks during the practical activity in the virtual power plant. One task asked the subject to select between two work locations that could be used to replace a filter. In this activity, the subject had to balance accessibility, judgment of hazards, and radiation levels at each location. Hazards included a series of barrels containing radiation sources and tight access to the second work location. Similarly, another task asked the subjects to choose between two paths through the radiation area. In this task, one path had very high radiation levels, but it provided a direct path to the goal. The second path provided lower radiation levels, but the path was much narrower. These tasks required the subjects to use their understanding of space, combined with their knowledge of radiation to come to the better answer.

The measurement error described the difference between the actual location of the radiation source and the location marked by the subject. The ability to locate a source in three-dimensional space was important since radiation fields vary in three-dimensions.
The dose maps that are included in typical work packages show only a two-dimensional variation, although the addition of head-level (HL) and knee-level (KL) tags to a dose map can provide some three-dimensional information. Asking subjects to mark the location of a source in space required them to perform a thorough three-dimensional survey, a task which would be impossible in any environment but a three dimensional one. On the measurement task, a small error denoted a thorough survey and an understanding that radiation sources could be above one’s head or below one’s knees.

The overall performance on the final assessment was gauged by considering the objective measures, described previously. Additionally, two tests were administered to evaluate the subject’s basic understanding of radiation awareness. A pretest asked questions about the basic concepts of radiation awareness and ALARA, focusing on time, distance, and shielding. In addition to conceptual questions, simple problems were designed to test the subject’s numerical understanding of the problem. A short post-test was administered to determine to what degree the subject had learned radiation awareness. The pre-test and post-test were similar in nature and problem-type to allow improvement to be measured. Performance differences between the two scores were designed to indicate how well the training transferred to the subject. More subjective measures were constructed from comments given by the subjects on the pre- and post-experiment surveys, as well as from observations made by the researcher.
Hypothesis Testing

Performance of the subjects in the two groups was compared using statistical methods for small sample sets: the T-Test, Analysis of Variance (ANOVA), and Cohen’s Effect Size (Cohen, 1998). Student’s T-Test is generally applied to compare the sample means of independently collected data sets. Using the T-Test, one can determine whether or not the differences in results between differing groups are statistically significant. A second test, the Analysis of Variance, provides a similar comparison between two or more data sets. In this case, the results were compared by training method – traditional CBT versus hands-on training using a simulated survey meter and activity-based virtual reality. Sample results were tested to determine whether or not one method significantly outperforms the other. Finally, effect size, which can sometimes reveal relationships between variables that are not apparent using other methods, was calculated.

The majority of the data collected during this experiment is quantitative. However, in an effort to paint a more complete picture, qualitative assessments were made based on the overall performance of each group, since each subject was carefully observed as he or she completed the training and assessment exercises. The qualitative information collected from surveys and observations was not scientifically assessed using a matrix or content analysis, *per se*, since not all subjects provided comments and the majority of responses were numerical. While this is true, the qualitative data was used to further explain some of the quantitative data, and it revealed additional information that does not show up directly in the quantitative data. Mixed methods, the use of both qualitative information collected from surveys and observations combined with
experimental data, are effective in lending context to collected data, allowing for a more complete analysis of results (Johnson & Onwuegbuzie, 2004).

**Pilot Study**

A pilot study was completed to test the experiment methodology. The pilot compared radiation awareness training using three different methods: computer based training, computer based training supplemented by a hands-on activity using a Teletrix radiation meter, and computer based training supplemented by an activity in a virtual radiation environment. The three methods were compared to determine which of the training methods resulted in a better understanding of factors affecting radiation exposure as demonstrated by the group’s performance of simulated activities in a virtual power plant and their scores on a post-experiment quiz. The following sections describe the methodology, subjects, and data collected for the pilot experiment.

**Pilot Experiment Participants**

Subjects for the pilot experiment were drawn from two pools – nuclear engineering students and architectural engineering students at Penn State University. The first pool represented personnel entering the workforce, because, as nuclear engineering students, these students had received varying amounts of training from Penn State’s Radiation Protection Office in order to receive a dosimeter at the Radiation Science and Engineering Center. Some subjects had received prior training in the US Navy. The
second pool, drawn from architectural engineering students, represented an untrained cohort.

The vast majority of subjects, 17 participants, were nuclear engineering students. Three subjects from architectural engineering participated in the experiment. A total of twenty subjects completed the experiment trials – seven completed the computer-based training only, six completed the hands on activity with the Teletrix simulated radiation meter, and seven completed the training activity in the virtual environment. Of the twenty subjects, two were female – one participated in the CAVE group and one participated in the CBT group. While twenty subjects completed the experiment trials, one male subject was removed from the virtual environment group, because he did not complete the computer-based training or the pre-experiment quiz prior to completing the activities in the virtual environment. This left six participants in the data set and nineteen total participants.

The subjects were randomly assigned to groups based on when they scheduled the virtual environment time. Drawing from the nuclear engineering major, groups were essentially balanced in age and experience; however, six of these students had prior experience as reactor operators and technicians in the US Navy. An attempt was made to balance the inclusion of these more seasoned subjects over the three groups. All other subjects were assigned randomly. Trials for the VR and CBT groups were completed first, and the Teletrix group was completed about a week later due to the availability of the Teletrix equipment.

Table 1 presents data for the three groups of participants in the pilot study.
The participants ranged in age from 18 to 28 years. The majority of subjects reported that hands-on was their preferred learning style, so it was expected that the activity-based training and practical assessment would be effective for instruction and measurement of their learning. About one-third of the participants had visited the CAVE previously, but none had controlled the environment prior to participation in the experiment.

**Pilot Experiment Overview**

The pilot experiment was conducted in four segments depicted in Figure 28. This experiment followed the flow described in the method section of this chapter. Copies of the documents, procedures, and tests used in the pilot experiment appear in Appendix B.

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### Table 1: Pilot Experiment Participants

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<th>CAVE (N=6)</th>
<th>Teletrix (N=6)</th>
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<td><strong>µ</strong></td>
<td>25.00</td>
<td>23.33</td>
<td>24.33</td>
</tr>
<tr>
<td><strong>σ</strong></td>
<td>2.38</td>
<td>3.33</td>
<td>2.66</td>
</tr>
<tr>
<td><strong>Age</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Badged for Access?</td>
<td>6 Yes, 1 No</td>
<td>6 Yes</td>
<td>3 Yes, 3 No</td>
</tr>
<tr>
<td>Learning Style</td>
<td>6 Hands-on, 1 Demonstration</td>
<td>4 Hands-on, 2 Other</td>
<td>4 Hands-on, 2 Demonstration</td>
</tr>
<tr>
<td>Visited CAVE?</td>
<td>2 Yes, 5 No</td>
<td>3 Yes, 3 No</td>
<td>2 Yes, 4 No</td>
</tr>
</tbody>
</table>
Pilot Experiment Discussion

The pilot experiment followed the framework discussed in the previous section. Each portion of the pilot is described further in this section.

The pretest and survey, examples of which appear in Appendix B, were designed to collect very basic information about the subject and to roughly determine their level of knowledge. The information collected from the survey was used during the data analysis phase to explain some of the performance results and expose possible biases. The results that follow were collected during the first twenty trials of the experiment.

Pilot Experiment Results

Using the methodology and data analysis methods described earlier, the pilot experiment provided some intriguing and unexpected results, which resulted in design
changes to the experiment and training activities for the follow-up trials. These design changes are described after the presentation of the results of the pilot study.

Table 2 provides the results of the two questions posed on the initial survey. The first question asked subjects to report their level of comfort with technology on a scale of one to ten. The second question asked subjects to report their familiarity with computers on a scale of one to ten. The mean and standard deviation for each of the three training groups is reported in the table.

Table 2: Pre-Experiment Survey Results for Pilot Study

<table>
<thead>
<tr>
<th></th>
<th>CBT (N=7)</th>
<th>CAVE (N=6)</th>
<th>Teletrix (N=6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comfort With Technology</td>
<td>µ</td>
<td>σ</td>
<td>µ</td>
</tr>
<tr>
<td>(10)</td>
<td>9.57</td>
<td>0.79</td>
<td>8.17</td>
</tr>
<tr>
<td>Computer Skills</td>
<td>8.57</td>
<td>1.27</td>
<td>8.17</td>
</tr>
</tbody>
</table>

The results of the survey showed an overall high level of comfort with technology and good computer skills for all groups. The CAVE group reported the lowest comfort with technology and the lowest computer skills. The difference in comfort with technology between the CAVE group and the CBT group is significant (p=0.074), and the difference between the CAVE and Teletrix group is also significant (p=0.17), if the relaxed interpretation of the T-test suggested by Winer (1971) is followed. The differences between the computer skills of the three groups were not statistically significant. The small difference between the survey results from the CAVE group to the other groups may account for some of the difference in performance on the assessment, the results of which appear later in Table 4.
Table 3 shows the mean and standard deviation of the data collected during the trials for the three training methods. Pre-test score, post-test score, study time for computer-based training, time spent performing supplemental training activities (Teletrix and Virtual Reality), and maze navigation time are presented.

Table 3: Results of Pilot Experiment

<table>
<thead>
<tr>
<th></th>
<th>CBT (N=7)</th>
<th>CAVE (N=6)</th>
<th>Teletrix (N=6)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>µ</td>
<td>σ</td>
<td>µ</td>
</tr>
<tr>
<td>Pretest Score</td>
<td>83.71</td>
<td>16.72</td>
<td>95.83</td>
</tr>
<tr>
<td>Posttest Score</td>
<td>87.29</td>
<td>14.28</td>
<td>91.67</td>
</tr>
<tr>
<td>CBT Time (min)</td>
<td>39.29</td>
<td>40.87</td>
<td>35.83</td>
</tr>
<tr>
<td>Training Time (min)</td>
<td>0.00</td>
<td>0.00</td>
<td>7.30</td>
</tr>
<tr>
<td>Maze Navigation Time (s)</td>
<td>424.57</td>
<td>61.75</td>
<td>384.17</td>
</tr>
</tbody>
</table>

Because most of the test subjects had received prior radiation awareness training from the U.S. Navy, internships, or through their education, their pre-test scores varied significantly. This was expected, but the large variance and poor performance of the Teletrix group was surprising. The post test scores show group-wide improvements in magnitudes and spread of data for the Teletrix and CBT groups, but the CAVE group did not show improvement. None of the pre-test to post-test changes were statistically significant, primarily due to the small sample size and large standard deviations (CAVE: p=0.397, CBT: p=0.676, Teletrix: p=0.525). Based on this data, it appears that little
learning took place as a result of the training the subjects received, since the magnitude of each change is masked by the large standard deviation. It is difficult to discern whether any progress was made because of the small sample size and varying levels of experience make quantifying it difficult.

The time spent on the computer-based training was approximately 45 minutes per group, although individual times varied greatly from zero to two hours. The additional training received by the CAVE and Teletrix groups ranged from five to eight minutes, so the additional training was only a small percentage of the total training time. The large variation should be expected for “self-paced” training class where subjects had differing learning speeds and levels of knowledge.

Considering the average maze completion time for each group, the large standard deviations in the data are most likely due to a few subjects getting lost in the maze, navigating through two and three times before finding the finish area. Most subjects completed the maze in five to six minutes. Based on the author’s prior experience with training hundreds of people to navigate in the CAVE, the time required to successfully navigate the maze was judged to be sufficient time to learn to navigate the virtual environment.

Table 4 presents data collected during the assessment activity for the three groups. The average radiation awareness score earned by each group is shown in the last row of the table. The data from the assessment reveals some interesting performance trends for each group.
The radiation awareness score was developed to combine the data collected during the assessment activity. The combined data resulted in the radiation awareness score, the magnitude of which is dominated by the four principal tasks completed by the subjects in the assessment. Each of the tasks was graded on a scale of 0 to 1. Additionally, the subject’s performance on the post-test and their dose per unit time were scored. The radiation awareness score was expressed as a percentage. As shown in Table 4, the highest radiation awareness was exhibited by the CBT-only group, and the lowest was exhibited by the CAVE group; however, the separation in the results between the three groups was not statistically significant. The difference between the average score for the CAVE group and the CBT group was not statistically significant (p=0.809),

Table 4: Assessment Scores for Pilot Experiment

<table>
<thead>
<tr>
<th></th>
<th>CBT (N=7)</th>
<th>CAVE (N=6)</th>
<th>Teletrix (N=6)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>µ</td>
<td>σ</td>
<td>µ</td>
</tr>
<tr>
<td>Dose (mrem)</td>
<td>2.05</td>
<td>2.32</td>
<td>1.97</td>
</tr>
<tr>
<td>Completion Time (s)</td>
<td>584.86</td>
<td>222.30</td>
<td>454.67</td>
</tr>
<tr>
<td>Hot Spot (mrem)</td>
<td>206.00</td>
<td>398.17</td>
<td>405.67</td>
</tr>
<tr>
<td>Source Found</td>
<td>0.57</td>
<td>0.53</td>
<td>0.83</td>
</tr>
<tr>
<td>Work Location Found</td>
<td>0.86</td>
<td>0.38</td>
<td>0.67</td>
</tr>
<tr>
<td>Path Selected</td>
<td>1.00</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Measurement Error (m)</td>
<td>1.84</td>
<td>1.69</td>
<td>2.35</td>
</tr>
<tr>
<td>Radiation Awareness Score</td>
<td>0.70</td>
<td>0.08</td>
<td>0.69</td>
</tr>
</tbody>
</table>
and neither was the difference between the CBT group and the Teletrix group (p=0.991). These numbers suggest that the activity-based training activities were ineffective. To further analyze the performances, the results from the CAVE group, since that is the medium of interest, can be further investigated.

The data shows that the average dose received by the CAVE group was substantially lower than either of the other groups. Combined with the faster completion time, one might guess that the CAVE group outperformed the other groups by completing the tasks quickly while receiving less radiation exposure. The analysis requires a deeper look.

The faster completion time exhibited by the CAVE group could suggest a comfort with the technology, a careless attitude approaching the training like a video game, or an understanding of radiation exposure reduction that is dominated by the time element of the ALARA concept. The CAVE group had approximately 5 to 7 minutes of additional time in the virtual environment due to their training being performed in the CAVE, so it is possible that they were more comfortable with the use of the CAVE. The video-game mentality results in an attitude where subjects believe they are in a video game where they cannot be harmed, radiation exposure is not real, and they concentrate solely on completing the task in the fastest time possible. In other words, the subjects have been unable to suspend their belief and become fully immersed in the training environment. It is also possible that the subject has allowed the time component of ALARA to dominate their perception of dose reduction techniques. Here, they complete all tasks as quickly as possible, limiting their dose, but perhaps not completing the tasks with the diligence and care they should.
Poor performance in the location of the radiation source in Area 5 and incorrect selection of the work location for the filter replacement task led to a radiation awareness score that was lower than the other groups. As scored, the work location task may be slightly unfair to the CAVE group since the task asks for hazards to be noted and for access to be considered when deciding upon the “correct” work location. Since radiation level at the two work areas varied by approximately 1 mR/hr, it is possible that the subjects decided that the difference in radiation level was not significant enough and that ease of access dominated their decision to select the “incorrect” work location. It is possible that the CAVE group had a better sense of their surroundings so they were able to more easily assess the access to the area. That said, the scoring for this task did not account for identification of hazards or the intent of the choice. The small difference in radiation level between the two work locations and the fact that no estimation was given for the duration of the filter replacement activity made this task difficult to complete.

The location of the hot spot in Area 5 was problematic for all groups; however, the CAVE group performed particularly poorly. To achieve a perfect score on this task, the subject had to locate the source with an error of less than one meter. The CAVE group exhibited the largest measurement error, which was recorded as the difference between the marked position and the actual position of the hot spot. The principal hot spot in the room was placed at head level inside of the third storage tank. A second source of a lower magnitude had been placed in the first storage tanks. This second source appeared to be the cause of the large measurement error. Many subjects marked this secondary source as the hotspot, since a conventional two-dimensional mindset would not detect a source placed at head-level. It was expected that the spatial
understanding gained by the CAVE group from the training they received would have led them to perform a more thorough three-dimensional survey, but this was not the case. It should be noted that the CAVE group’s subjects reported the lowest skill with computers and comfort with technology. This fact may account for some of the performance difference between the CAVE group and the others.

Table 5 presents the data collected from the post-experiment survey. The survey asked five questions, a summary of each appears in the left column. The mean and standard deviation for the CBT, CAVE, and Teletrix groups are presented in the other columns.

<table>
<thead>
<tr>
<th></th>
<th>CBT (N=7)</th>
<th>CAVE (N=6)</th>
<th>Teletrix (N=6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ease of Learning Virtual Environment (10)</td>
<td>7.86</td>
<td>8.17</td>
<td>8.83</td>
</tr>
<tr>
<td>Understanding of Time and Distance (10)</td>
<td>9.71</td>
<td>9.67</td>
<td>8.83</td>
</tr>
<tr>
<td>Helpfulness of Practical Exercise (10)</td>
<td>8.29</td>
<td>9.17</td>
<td>8.50</td>
</tr>
<tr>
<td>Helpfulness of CBT (10)</td>
<td>6.86</td>
<td>7.50</td>
<td>7.17</td>
</tr>
<tr>
<td>Performance on Assessment (10)</td>
<td>6.86</td>
<td>8.17</td>
<td>6.33</td>
</tr>
</tbody>
</table>

The first question asked about the ease of learning to operate the virtual environment. A score of one represented impossible to learn, and a score of ten meant they felt the virtual environment was easy to learn. The survey responses showed the subjects felt the virtual environment was fairly easy to learn. The Teletrix group felt it
was the easiest, and the computer-based training group felt it was slightly more difficult. Subjects giving the ease of learning a lower score pointed out the fact that they could walk through walls detracted from the ease of use.

The second question asked about their understanding of the time and distance components of the ALARA concept. On this question, a score of one represented no understanding, and a score of ten represented complete understanding of the concept. All groups felt they exited the training with a very good understanding of the time and distance concepts of ALARA. The majority of the subjects came from nuclear engineering, and they had studied the ALARA concept before. Since they came into the experiment with a good understanding, the training activities reinforced knowledge they already knew, which explains the high score on the survey question.

Next, the survey asked the helpfulness of the practical exercise. Scoring on this question ranged from one, meaning the practical exercise was useless, to ten, meaning the practical exercise was very helpful. The practical exercise was designed to enable the subjects to put what they had learned from the training into practice, and based on their responses, all subjects seemed to find the exercise to be helpful. While they found the practical exercise to be helpful, all of the subjects had lower opinions of the computer based training.

The fourth question asked the subject’s opinion of the computer based training. A score of one meant the subject felt they learned nothing, and a score of ten meant the computer based training gave them complete understanding of the concepts. The group that completed only the computer based training had the lowest opinion of that form of training. The groups that received the supplemental training using the virtual
environment or the simulated meter found the computer based training to be slightly more helpful, but the spread in the data indicates that there were some differing opinions.

The last question on the quiz asked the subject for a self-assessment of their performance on the assessment activity in the virtual power plant. A score of one on this question meant the subject had no confidence in their performance, and a score of ten meant the subject felt they performed very well on the activity. The group that received only computer based training felt they had performed just slightly above average, which the virtual reality group had the most confidence in their performances. The Teletrix group also had increased confidence in their performances. Based on those numbers, it appears that the two groups that received the additional training felt more confidence in their performance on the final assessment.

**Analysis**

In watching the experiment unfold in real time, it became obvious that the analysis of the statistics would not tell the complete story of the training activity. The results of the pilot study revealed information about the subjects and the design of the experiment as well as the suitability of the radiation awareness training.

The subjects that participated in the pilot experiment began with varying levels of experience in working in a radiation environment. This variance in experience made it difficult to quantify which subjects had learned, which subjects had not learned, and which subjects had plateaued. For example, the CAVE group outperformed both of the other groups on the pre-test and the post-test, but the group’s average performance on the
post-test was poorer than on the pre-test. In this case, it was difficult to improve upon an average score of 95, suggesting that knowledge had plateaued prior to completing the training.

Subjects also exhibited varying levels of spatial ability and awareness as evidenced by the large differences in maze completion times. Some subjects became quite disoriented in the maze, even with landmarks inserted to assist them. Subjects with better spatial abilities were expected to perform better in the virtual environment since it is designed to accurately portray a realistic 3-D environment. Some of the disorientation in the maze may have been a result of the fact that it was possible to walk through the walls. When this occurred, the subject was notified and was assisted in returning to the point where they broke through. For the final experiment described in the next chapter, a collision detection algorithm was utilized to prevent similar occurrences.

The subjects reported differing levels of comfort with technology. The CAVE group reported the lowest level of comfort with technology. Apprehension associated with using technology for training can distract the user, causing them to concentrate more on the technology and less on the concept being taught. This apprehension can cause performance to suffer, resulting in negative training where performance after training is actually worse than it would have been with no training.

Results also showed a disconnect between the subjects’ performances on the paper tests and their performance on the assessment in the virtual environment. The majority of the subjects performed very well on the post-test suggesting that the computer-based training that all participants received was effective at presenting the information necessary for the written examination. Subjects did not perform nearly as
well in the simulated radiation environment, with only four subjects from the pool of twenty successfully completing all of the tasks, with only an additional six subjects completing three of the four tasks. The tasks were designed to be challenging, forcing the subjects to apply their understanding of the properties of radiation. However, it appears that the additional training proved ineffective and may have even provided negative training, although this could be due to the design of the training activity rather than the technology used. This question is examined further below.

The performance of the subjects on the assessment led to some interesting questions:

- Did training allow sufficient time for information to be retained?

The participants were asked to complete the computer-based training activity on their own time, prior to coming to the CAVE for either additional training (Teletrix and CAVE groups) or for the assessment (CBT group). The time elapsed between the completion of the CBT and the assessment could have allowed the subject to reflect upon the information and to encode it or to read it and forget it. The additional training activities performed by the Teletrix group and the CAVE group were completed only minutes before the assessment. It is possible that the subjects did not have time to internalize the concepts that they had practiced in the activity-based training. Additional time for reflection should be provided, if requested.

- Was the training too scripted?

The training activities used to train the time and distance concepts were developed taking into account the features and limitations of the Virtual Reality system and the Teletrix meter. To make a fair comparison between the two methods, the training
activities had to be as similar as possible. Because of this, the activity developed was very limited in scope. The reading test and the distance test were designed to be exactly the same in both environments, which limited the subject’s ability to explore and complete the activity. One of virtual reality’s principle advantages is its ability to safely expose users to situations that would be too dangerous to experience otherwise and to allow them to explore the situation. The forced similarity between the two training methods created a situation that severely limited the capabilities of the individual in the virtual reality training environment to fully utilize and explore the virtual environment.

- Did the training make use of discovery learning principles?

Since the training was essentially the same in the two environments, there was little flexibility in the design of the environment. The intent of discovery learning (constructivism) is to provide the learner with an environment where they have the tools and activities needed to take what they have learned previously and construct an understanding that is consistent with their previous knowledge. The subjects in the pilot study had been exposed to the basics of radiation awareness through the computer-based training. The activity based training used in the pilot study did not provide enough flexibility to generate the deeper understanding expected.

As Table 2 shows, the CAVE group reported lower comfort with technology and less skill with computers than either of the other groups. If comfort with technology and computer skills can be used to predict performance in the simulated radiation environment, one would predict that the computer-based training and Teletrix groups would perform well, while the CAVE group lagged behind. As Table 4 shows, the computer-based training group performed the best overall on the assessment, while the
CAVE group and Teletrix group performed similarly. Based on those results, comfort with technology and computer skills are not necessarily the best predictors of performance on the assessment.

**Pilot Study Findings**

Ideally, subjects would complete a practical exercise in the environment where they received their training – the personnel who received hands-on training in the real-world environment would be assessed in a real-world task, and the personnel who received hands-on training in the virtual environment would perform the same task in a virtual environment. This is the only way to directly ensure that some subjects do not have an advantage over others introducing an unwanted bias into the experiment. Unfortunately, the real-world environment is not a viable option in this instance, due to the absence of reliable, physics-based simulated dosimetry. The lack of dosimetry eliminated one of the most significant chosen measures of effectiveness, radiation dose. In addition, it is not desirable to assess the subjects in an actual radiation environment due to the hazardous nature of the radiation environment.

Because all groups were assessed in the virtual environment, special consideration must be given to the additional experience achieved by the group that received all of their training in the virtual environment. Some of this potential bias was alleviated by providing all subjects the opportunity to complete the navigation training for a second time after they received the radiation awareness training. Based on the investigator’s years of experience with introducing novice users to the technology, most users grasp the
control of the virtual environment quickly and almost immediately recover their navigation skills after periods of non-use. The additional time the VR-trained group spent in the virtual environment was small, and it is believed that it did not provide a substantial advantage during the performance of the assessment. One could argue that the VR environment is the best place to perform the assessment because of its ability to safely simulate and record simulated radiation exposure, as well as providing a controlled and repeatable environment that ensures that each subject experiences the same situation. While the training environment can be tightly controlled, the prior experience that each subject brings into the training environment cannot. As the learning theory section discussed, prior knowledge can be an important consideration in whether or not training is transferred.

Based on the results of the pilot experiment, a number of improvements were made to the experiment to address some of the shortcomings of the experiment design. First, the resultant experiment compares the performance of only the computer-based training and the CAVE virtual environment. All subjects in subsequent experiments will be drawn from a pool of equally untrained people, since it was difficult to assess training-based learning as the improvement observed in the subjects’ performances was so small due in part to their prior knowledge. Additionally, a larger number of subjects completed the experiment trials. When combined with the decision to run only the CBT and CAVE groups, the statistical results were expected to be more accurate. Since the activity-based training appeared to show no effect, the training activity was re-designed to make better use of discovery learning concepts. Finally, an algorithm that prevented subjects from walking through walls was implemented. This removed one of the most significant
detractors mentioned by subjects during the experiment trials. The improvements to the experiment are discussed further in the introduction of the next chapter.

Summary

Training theory and virtual reality technology were combined to develop an assessment of radiation awareness using virtual reality. To test the hypothesis that subjects who received activity-based training in a virtual environment would demonstrate a higher level of radiation awareness, a pilot study was executed. Subjects were assigned to three groups, and each group received training using a different method. All groups received computer-based training by reading through a PowerPoint slide show and a PDF document. The control group received no further training, while the other groups received hands-on training using a Teletrix simulated survey meter or were trained in a virtual environment. Once they had received the training, the subjects performed a hands-on assessment in a virtual mockup of a simulated nuclear power plant space.

A variety of data was collected before, during, and after the assessment activity. Survey results revealed similar levels of computer skills, but the CAVE group lagged in comfort with technology. The CAVE group, on average, completed the assessment activity in the fastest time, while receiving the lowest radiation exposure. However, the group fell short in the source location task and the work location selection task, causing them to score the lowest radiation awareness of the three groups tested. That said, all groups were within statistical uncertainty of each other, so the activity-based training as
executed was deemed to be ineffective. This led to multiple changes to the design and execution of the experiment, which are discussed in the next chapter.
Chapter 7

Experiment

This chapter presents data collected during the second radiation awareness experiment. The pilot experiment revealed a significant amount of information regarding the experiment design, which led to many improvements in the final experiment. The revised experimental method is described in the next section, while the rest of the design changes are discussed in the sections which follow.

Method

The methodology used for the final experiment design was very similar to that used in the pilot study described in the previous chapter, but a few improvements were made to the experiment based on the pilot findings to increase the ease of use of the CAVE, make the VR training more effective, and improve the quality of the data collected. The software used to create and display the virtual environment was upgraded to run updated versions of Explorer and Vega Prime, additional stations were added to the VR training activity, and the CAVE training activity was re-designed to accommodate the changes in the CAVE software.

The improved experiment featured only two groups of participants, since the Teletrix group did not show a significant performance difference in the pilot experiment. The elimination of the third group decreased the statistical variance of the experiment by
dividing the 23 participants between two groups, rather than three. The participants in
this experiment were assigned to either the computer-based training only group or the
CAVE group.

Figure 29 shows the updated flow for the experiment. Participants began by
completing the survey of demographic data. Second, they completed a pretest which
gauged their pre-training knowledge, and then all participants completed a computer-
based training program. Next, the subjects received initial orientation training in the
CAVE using the navigation training maze as was discussed in the previous chapter.
After they completed the navigation training, the subjects assigned to the CBT-only
group proceeded directly to the assessment activity in the virtual power plant while the
subjects in the CAVE group received supplemental radiation awareness training in the
CAVE prior to completing the assessment activity. When the final assessment was
concluded, the subjects completed a post-test to gauge their post-training knowledge and
an additional survey to compile information on their experience.

![Figure 29: Experiment Flow](Image)

After completion of the pilot study, the software programs used to develop and
display the data in the CAVE were updated, altering some of the capabilities available in
the full-scale virtual environment. The addition of a collision detection algorithm to the
motion model made it possible to prevent users from walking through the walls in the navigation training maze and during the assessment activity in the virtual power plant. The collision detection feature removed one of the distractions that was most often cited by the participants in the pilot study, that of being able to walk through walls and become disoriented.

The updated software also improved the capabilities of the radiation dose model. After the update, radiation sources could be attached to objects in the virtual environment, enabling more dynamic radiation environments to be created. A demonstration of this capability was used in the virtual training environment. Another update to the radiation dose model adjusted the positioning of the radiation level and dose received readouts, so that they could to be attached to the virtual radiation meter. This capability made the detector easier to read while the user was measuring radiation levels since the text followed the movements of the Wand controller.

Improvements made to the VR training activity are discussed in the following section.

**VR Training Activity**

Those who received the CAVE training were exposed to a new virtual environment, a top view of which is shown in Figure 30. This environment was created to improve the virtual reality training activity by adding activity-based training stations that were developed with constructivist principles in mind. Upon entering the CAVE for training, test subjects had already received computer-based training, intended to provide a
basis upon which the VR activity could build. This enabled the subjects to use the supplemental training to construct a deeper understanding of the radiation awareness concepts. Five stations were created to reinforce portions of the concept of radiation awareness discussed in the computer-based training.

![Top view of VR Training Environment](image)

Figure 30: Top view of VR Training Environment

The first station completed by the subjects, shown in Figure 31, was designed to demonstrate the relationship between distance and radiation exposure. Five markers were placed in one-meter intervals at increasing distances from a barrel containing a radiation source. Subjects were instructed to measure the radiation level at each marker location and at the top of the barrel. Each measurement was recorded on a worksheet. Once the task was complete, the subjects were asked to write down and then verbally describe
what they had observed. The subjects were expected to describe a small increase in the radiation level for the first few measurements and a more dramatic increase for the measurements that were closest to the source. The computer-based training discussed the inverse-square law in the intensity of radiation, so the activity was designed to demonstrate and reinforce this concept.

Figure 31: Dose-Distance Activity

Figure 32 shows the activity that was created to demonstrate the relationship between time and dose. This activity required subjects to place and hold their survey...
meter in a single location while reading two passages aloud. The first passage, which required approximately one minute to read, was Robert Frost’s poem “The Road Not Taken.” The second passage, which required approximately two minutes to read, was the second paragraph of the U.S. Declaration of Independence. As participants paused to read the passages, they accumulated radiation exposure. On their worksheet, the subjects recorded the time spent reading, the radiation level in milli-Roentgen per hour, and the radiation dose received in millirem. Once they had completed the activity, the subjects were asked to look at the results they had recorded and to describe what they had observed. The desired response was that the dose had doubled when the time doubled, creating a linear relationship between time and dose. To reinforce this knowledge, the subjects were then asked to calculate the resulting dose from a four-fold increase in time. Once they had correctly described the concept, they were cleared to move on to the next activity.
The third station, shown in Figure 33, enabled the subjects to measure the geometry of a single source. Concentric circles surrounding a radiation source were color coded based on the radiation level: green representing the lowest radiation level and red representing the highest. Subjects were instructed to walk around the green circle, while paying attention to the radiation reading on their meter. Since the circles were intended to be iso-dose curves, the subjects were expected to see that the dose did not change as they walked around the circle. Once they had verbalized understanding of that concept, they were asked what they thought would occur if they repeated the walk for the yellow circle. They were expected to respond that the radiation level would not change as they walked around that circle, but the magnitude would be higher, as it would be closer to the source. Once this concept was understood, the subjects were asked to run the survey
meter over the red sphere in the center. If the task was performed correctly, the radiation readings would be the same over the surface of the sphere. This activity was designed to show the subject that radiation varies in three dimensions. Once this concept was clear, the subject proceeded to the next station.

The next station (Figure 34) was intended to show the subject the rate of change of the radiation level. At this station, the subject was directed to stand at the “stand here” sign and hold up their survey meter. The barrel in the image below was set to move along a five meter path. At the end of the path, the source containing barrel switched directions and moved in the opposite direction. As the barrel moved toward and away
from the subject, the radiation level changed. The subjects were asked to watch the change in the radiation level as the barrel moved along its path. They were expected to notice that the radiation level changes quickly when the source is close to them and more slowly as the source is farther away, since the radiation level changes relative to an inverse square of the distance. When the subject verbalized this concept, they were free to proceed to the final station where they were to apply what they had learned.

Figure 34: Rate of Change Activity
The final station, depicted in Figure 35, enabled the subjects to put the concepts they had learned into practice. Two radiation sources were placed inside of a mockup of two tube-in-shell heat exchangers. Subjects were instructed to stand on the “stand here” marker and to survey the radiation levels around the mockup. Once the survey was complete, the subjects were asked to use their judgment to determine where the best place to stand and read the pressure gauge would be if they were going to be there for an extended period of time. The radiation level was strongest towards the center of the mockup, so the best place to stand would be about 2 feet back from the mockup and 2 feet to the right of the gauge.

Figure 35: Site Survey Activity
After the final station, the subjects were informed that their radiation awareness training was complete, and they proceeded to the assessment activity.

**Assessment Activity**

To assess their learning in a more authentic way, all subjects completed an assessment activity in which they performed four tasks in a virtual radiation environment. The tasks used for the assessment activity were streamlined after the pilot experiment was completed to make the directions easier to follow. Similar to the pilot experiment, the subjects were provided with a sheet of instructions, a plan-view of the power plant, and an out-of-date dose map. They were given ten minutes to study the information and develop a plan before they entered the virtual power plant. When they had completed their planning, the subjects put on the glasses and took the controller into the CAVE, prepared to complete the activities in the virtual power plant (Figure 36).
In the first area shown in Figure 37, the subjects were directed to locate the highest radiation reading in the room and to report that number to the control room. The room contained a large number of barrels and two radiation sources. The strongest source was placed in the middle barrel in the last row. A cursory study of that row would locate the source. The second source was placed in one of the central barrels in the arrangement. This barrel would only be located if the subject squeezed in between the barrels. In this experiment, a collision detection algorithm was implemented that
prevented subjects from walking through the walls of the plant. This algorithm also made it difficult to walk between the barrels, which made the location of the second source more difficult. In addition to the changes in the collision detection and source profiles, a radiation area sign was added to trigger the subject’s increased radiation awareness.

![Figure 37: Task 1 Location](image)

**Task 2**

The second area, shown in Figure 38, required the subjects to choose a work location, A or B, for a filter replacement task. The candidate work locations were marked
on the floor with signs reading “A” and “B.” Subjects were also asked to note any hazards around the work location. The source profile for this task was modified from its initial location in the pilot study to create a more 3-Dimensional variation in radiation level. Stronger radiation sources were placed in the barrels along the side of the room. A strong radiation source was placed at head level in the tank at the back of the room next to location “B”. These changes resulted in location “A” having lower radiation levels. Because of this, it was designated to be the safer place to work.
Task 3

The third task entailed choosing between two possible paths that a worker would have to traverse to access a room in the virtual power plant. The two paths were of similar length, but the path labeled “A” had significantly higher radiation levels than path “B.” The subjects traversed each path, reading the radiation levels as they walked. At the end, they selected a path based on the data they observed. The entrance to Path A is shown in Figure 39.

![Figure 39: Path Selection Task](image)

Minor changes were made to this task after the pilot. First, a radiation area sign was placed at the beginning of path “A” where previously there was none. Second, paths
“A” and “B” were labeled with placards on the floor at the entrance to each path to make it easier for the subjects to know which path they were following. Third, the radiation source distribution was changed by increasing the magnitude of the hot-spot on path “A.” These alterations were made to force the subject to carefully choose the correct path.

**Task 4**

The final task completed by the subjects required them to locate and estimate the magnitude of a hot spot. The subjects were expected to enter the last room and survey an area to locate the hot spot. The strongest source was placed above head level in the third storage tank in an attempt to test whether or not the subject understood the need to perform a three-dimensional survey. The hot spot is shown in Figure 40.
The fourth task was changed only slightly after the pilot study. The source in the third tank was strengthened to create a true distinction in the radiation readings in the room. Also, scoring of the task was changed to accommodate the loss of the ability to mark source location after a software upgrade. Because of this, the new task required the user to verbally identify the relative location of the hot spot. The subjects were asked to estimate the magnitude of the source so the dose map of the area could be updated.
Experiment Participants

Twenty-three adults ranging in age from 19 to 47 participated in the experiment. Eleven participants served as the control group, completing only computer-based training. Twelve participants completed the computer-based training supplemented with an activity based training exercise in the virtual environment. Each participant received ten dollars in compensation for their participation, which lasted approximately two hours. Approximately one hour was spent on the computer-based training, and approximately one hour was spent on the VR training (if assigned) and assessment-related activities. Participants were randomly placed into one of these two groups based on scheduling availability.

Results

The results of the experiment are presented in the following section. The changes made from the pilot for the final experiment resulted in an outcome where performance improvement was easier to quantify.

The data collected for the experiment included both quantitative and qualitative information. Pre-experiment survey responses, a pre-test, time spent performing training, assessment activity results, post-experiment survey responses, and post-experiment quiz results were collected for each of the twenty-three participants. Average results for the control group and the CAVE trained group are presented in this section.
Pre-experiment Survey

The first data collected were the subject’s responses to the pre-experiment survey. The survey consisted of questions to give the researcher an idea of each subject’s experience level and familiarity and comfort with technology. Results of this survey appear in Table 6.

<table>
<thead>
<tr>
<th>Table 6: Pre-Experiment Survey Results</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CBT (N=11)</strong></td>
</tr>
<tr>
<td>µ</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td><strong>Age</strong></td>
</tr>
<tr>
<td><strong>Learning Style</strong></td>
</tr>
<tr>
<td><strong>Visited CAVE?</strong></td>
</tr>
<tr>
<td><strong>Comfort With Technology (10)</strong></td>
</tr>
<tr>
<td><strong>Computer Skills (10)</strong></td>
</tr>
</tbody>
</table>

The survey showed a difference of approximately 2.4 years in age between the two groups of participants. Ages in the CBT group ranged from 21 to 38 years, while the CAVE group ranged from 19 to 47 years. The majority of subjects in the CBT group (8) reported a preference for hands-on learning, while the three other respondents preferred learning by reading books or procedures. These three participants should have been particularly comfortable learning from the CBT. In the CAVE group, eleven participants reported that they preferred hands-on learning, while a single respondent preferred watching demonstrations. This group should have been particularly suited to learning in
the virtual environment. Differences between the two groups with respect to their level of comfort with technology and similar proficiency with computers were not significant.

Pre-test

The pre-test was designed to assess the subject’s level of knowledge and understanding prior to completing any training. The pre-test consisted of six questions which queried understanding of definitions, concepts, and calculations. Table 7 presents the question-by-question scores for the CBT and CAVE groups. The final score, a percentage based on six total points, is also presented. Raw scores are tabulated in Appendix C.

<table>
<thead>
<tr>
<th></th>
<th>CBT (N=11)</th>
<th>CAVE (N=12)</th>
<th>T-Test</th>
<th>Effect Size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>µ</td>
<td>σ</td>
<td>µ</td>
<td>σ</td>
</tr>
<tr>
<td>ALARA</td>
<td>0.09</td>
<td>0.30</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>3 Components</td>
<td>0.35</td>
<td>0.42</td>
<td>0.23</td>
<td>0.27</td>
</tr>
<tr>
<td>Meter Reading</td>
<td>0.45</td>
<td>0.52</td>
<td>0.58</td>
<td>0.51</td>
</tr>
<tr>
<td>Double Distance</td>
<td>0.55</td>
<td>0.52</td>
<td>0.50</td>
<td>0.52</td>
</tr>
<tr>
<td>Dose Received</td>
<td>0.41</td>
<td>0.49</td>
<td>0.67</td>
<td>0.49</td>
</tr>
<tr>
<td>Path Selection</td>
<td>0.91</td>
<td>0.30</td>
<td>0.83</td>
<td>0.39</td>
</tr>
<tr>
<td>Score</td>
<td>0.46</td>
<td>0.25</td>
<td>0.47</td>
<td>0.21</td>
</tr>
</tbody>
</table>
Both groups’ subjects’ performances on the pre-test were the same within uncertainty, showing comparable levels of knowledge. Only one question, which asked the subjects to calculate the dose received given the strength of the radiation field and the amount of time spent in the environment, approached a significant difference. The similar performance on the pre-test enabled the learning achieved via the computer based training and supplemental VR training to be quantified.

Training

The two groups of subjects received radiation awareness training. The computer-based training consisted of a 62-page PDF document and a 30-slide PowerPoint presentation. All participants completed the computer-based training. The second group of 12 subjects completed activity-based training in the virtual environment. The respective training times for both groups are presented in Table 8 below.

Table 8: Training Time for CBT and Supplemental Training

<table>
<thead>
<tr>
<th>Time Type</th>
<th>CBT (N=11)</th>
<th>CAVE (N=12)</th>
<th>T-Test</th>
<th>Effect Size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>µ</td>
<td>σ</td>
<td>µ</td>
<td>σ</td>
</tr>
<tr>
<td>CBT Training Time</td>
<td>1:20:00</td>
<td>0:43:04</td>
<td>1:14:10</td>
<td>0:31:54</td>
</tr>
<tr>
<td>Additional Training Time</td>
<td>0:00:00</td>
<td>0:00:00</td>
<td>0:14:15</td>
<td>0:01:48</td>
</tr>
</tbody>
</table>

The two groups studied the computer based training materials for an hour and twenty minutes (CBT-only) and an hour and fourteen minutes (CAVE), a difference that was not significant. The CAVE group performed the five supplemental training activities
discussed in the previous section in an average of just over fourteen minutes. The additional training time the CAVE group received should not be significant since the subjects were encouraged to spend as much time as they needed on the computer-based training. It is assumed that the performance differences between the two groups should be dominated by the change in training method, rather than the additional time, although the only way to prove this would be to fix the total training time. That was not done in this case.

**Assessment**

The assessment activity was designed to test the subject’s understanding of radiation awareness concepts. Typical assessments in utility plant access training (PAT) and radiation worker training (RWT) are comprised of written examinations solely, which test only declarative knowledge. These tests do not assess the learner’s ability to apply the skills which the trainers intended to be transferred from reading the manuals. This assessment was designed to test the subject’s application of what they knew in a simulated radiation environment. The subjects completed four tasks ranging from locating a radiation source to choosing a path in a virtual power plant. Each task was graded on a scale of zero to one. In addition to the four tasks, the subject’s dose was scored, as well as their completion time. The dose and the completion time were scaled based on the best performances observed during this trial. The best performance (fastest time, lowest dose) in each category earned a score of 1.0, and all other performances were scored relative to that top performance. The final component of the radiation
awareness score was the subject’s performance on the post-experiment quiz. All of these quantities were combined to calculate a radiation awareness score. The average performance on each task for both groups is shown in Table 9.

Table 9: Assessment Performance

<table>
<thead>
<tr>
<th></th>
<th>CBT (N=11)</th>
<th>CAVE (N=12)</th>
<th>T-Test</th>
<th>Effect Size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>µ</td>
<td>σ</td>
<td>µ</td>
<td>σ</td>
</tr>
<tr>
<td>Dose Received (mrem)</td>
<td>3.38</td>
<td>3.97</td>
<td>1.69</td>
<td>0.91</td>
</tr>
<tr>
<td>Completion Time (h:m:s)</td>
<td>0:09:21</td>
<td>0:03:22</td>
<td>0:08:21</td>
<td>0:02:49</td>
</tr>
<tr>
<td>Area 1 Reading (mR/hr)</td>
<td>185.01</td>
<td>280.05</td>
<td>43.49</td>
<td>45.96</td>
</tr>
<tr>
<td>Task 1 Score</td>
<td>0.73</td>
<td>0.47</td>
<td>0.50</td>
<td>0.52</td>
</tr>
<tr>
<td>Task 2 Score</td>
<td>1.00</td>
<td>0.00</td>
<td>1.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Task 3 Score</td>
<td>1.00</td>
<td>0.00</td>
<td>1.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Task 4 Reading (mR/hr)</td>
<td>34.64</td>
<td>36.21</td>
<td>31.33</td>
<td>15.40</td>
</tr>
<tr>
<td>Task 4 Score</td>
<td>1.00</td>
<td>0.00</td>
<td>1.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Dose Score</td>
<td>0.41</td>
<td>0.22</td>
<td>0.57</td>
<td>0.27</td>
</tr>
<tr>
<td>Time Score</td>
<td>0.67</td>
<td>0.19</td>
<td>0.72</td>
<td>0.19</td>
</tr>
<tr>
<td>TOTAL RA Score</td>
<td>0.79</td>
<td>0.06</td>
<td>0.80</td>
<td>0.10</td>
</tr>
</tbody>
</table>

The results show some performance differences on individual tasks, but the overall performance of the two groups, as shown by the radiation awareness score, is remarkably similar. While scores were equal for task 2 (the work location selection), task 3 (the path selection), and task 4 (the hot spot location), there were distinctions in the performances of the two groups on the first task, where they were asked to locate the hot
spot in the first room. The CAVE group did not score as well on the first task, since a number of subjects did not perform a thorough survey of the area. Possible reasons for this difference in performance will be analyzed further in later sections of this dissertation, but the effect size predicted a medium effect of the training; however, in this case, it was in the negative direction. Subjects in the CAVE group measured a lower maximum radiation level, and the difference was nearly statistically significant (p =0.13). These results suggested that the subjects in the CAVE group had developed a sensitivity to radiation, but had not yet internalized the difference between normal exposure and unnecessary exposure. Results on this task might suggest that negative training occurred because the subjects in the group receiving the supplemental training did not complete the task. While true, the subjects were not trained to complete the tasks or to perform proper surveys; they were trained to reduce radiation exposure, avoiding unnecessary exposure. The subjects successfully completed this portion of the task.

Additional performance differences were apparent in the time score and the dose score. The time score was a measurement of how quickly the subjects completed the four tasks and exited the plant. The CAVE group completed the tasks an average of one minute faster than the CBT group, although the result was not statistically significant (p=0.45) because of the large standard deviations. A calculation of the effect size showed that the CAVE training had a small-to-medium effect (d=0.32) in reducing completion time, however. The dose score was a measure of the subject’s success in avoiding radiation exposure and completing the tasks quickly yet deliberately. Again, the CAVE group performed better by scoring higher; driven by the lower dose received. If the dose received by the two groups is compared, the T-test shows a difference that is nearly
significant (p=0.13), and the effect size shows the additional training had moderate effect (d=0.65) on reducing radiation exposure. Because the overall radiation awareness scores are so close, other measures must be used to determine whether the VR training was worthwhile, although the faster completion time and lower radiation exposure are promising.

**Post Test**

Table 10 presents the results of the post-test, which all subjects completed after the computer-based training, supplemental training (CAVE group), and the assessment activity in the virtual environment. The six-question quiz was designed to be similar to the pre-test that was completed initially, although the post-test was intended to be slightly more difficult. A combination of theory questions, definitions, and calculations, the quiz was designed to be representative of the assessments currently being performed by utilities. A copy of the exam and the raw results are provided in Appendix C.
The post test results show improvement in the test scores of both groups. The subjects did not perform well on the first question, the definition of ALARA, which required them to memorize an acronym. Most subjects in the CBT group correctly identified the 3 components of ALARA as time, distance, and shielding, while slightly more than three-quarters of the CAVE group’s subjects answered the question correctly. The difference in these results was significant (p=0.05), and the training had a large effect as demonstrated by the effect size of 0.85. Performance on the meter reading question was poor. This is most likely due to the estimation of a square root that was required by the calculation, rather than a lack of knowledge of the concept. In this case, the difference was not statistically significant. All subjects correctly calculated the dose a worker would receive given a time and a dose rate. Approximately two-thirds of the subjects correctly answered the arithmetic path selection, and the difference was not

<table>
<thead>
<tr>
<th>Table 10: Post Test Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>ALARA</td>
</tr>
<tr>
<td>Time, Distance, Shielding</td>
</tr>
<tr>
<td>Meter Reading</td>
</tr>
<tr>
<td>Dose Calculation</td>
</tr>
<tr>
<td>Path Selection (Arithmetic)</td>
</tr>
<tr>
<td>Path Selection (Graphical)</td>
</tr>
<tr>
<td>Score</td>
</tr>
</tbody>
</table>
statistically significant. This question was designed to show that sometimes traversing a path with higher radiation levels may result in a lower radiation exposure. Finally, the subjects were asked to graphically estimate which path would result in the lowest radiation exposure. All subjects from the CAVE group correctly answered the question, while approximately three-quarters of the CBT group answered the question correctly. This might suggest that the CAVE group had a better spatial understanding of the properties of radiation, while the group that was trained only using the CBT seemed to score better on the questions asking them to demonstrate declarative knowledge. The result of the post-test was that the CAVE group outperformed the CBT group by three percentage points, a difference that was not statistically significant (p=0.652).

Post Experiment Survey

Table 11 shows the results of the post-experiment survey completed by all the subjects. The survey measured the subjects’ attitudes about the experiment after all portions had been completed. Ease of learning the virtual environment, the subject’s self-assessment of understanding of time and distance, the helpfulness of the practical exercise, the helpfulness of the computer-based training, and finally a self-assessment of performance were measured. Data for the CBT and CAVE groups is provided, and the survey and raw response data are provided in Appendix C.
The results of the post-experiment survey show that both groups felt the virtual environment was easy to learn to operate. The CAVE group felt they had a better understanding of time and distance than the CBT group, and the result was nearly significant (p=0.09), while the effect size calculation for this question might suggest that the supplemental training in the CAVE generated a medium-to-large effect (d=0.74). Both groups felt the practical exercise was helpful, but the CAVE group felt so more strongly, although the difference in the result was not significant (p=0.3). The participants felt the CBT was less helpful than the practical exercise, and again, the CAVE group felt more strongly this way. Finally, when asked to rate their performance, the subjects felt they had performed “well” but not “excellent.” The CAVE group appeared to have slightly more confidence in their performance, although the result is not significant.

Table 11: Post-experiment Survey

<table>
<thead>
<tr>
<th></th>
<th>CBT (N=11)</th>
<th>CAVE (N=12)</th>
<th>T-Test</th>
<th>Effect Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ease of Learning VE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>µ</td>
<td>8.45</td>
<td>8.33</td>
<td>0.88</td>
<td>0.06</td>
</tr>
<tr>
<td>σ</td>
<td>1.86</td>
<td>1.92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Understanding of Time and Distance</td>
<td>8.27</td>
<td>9.33</td>
<td>0.09</td>
<td>0.74</td>
</tr>
<tr>
<td>Helpfulness of Practical</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>µ</td>
<td>8.36</td>
<td>9.00</td>
<td>0.31</td>
<td>0.44</td>
</tr>
<tr>
<td>σ</td>
<td>1.36</td>
<td>1.54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Helpfulness of CBT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>µ</td>
<td>6.91</td>
<td>6.42</td>
<td>0.65</td>
<td>0.19</td>
</tr>
<tr>
<td>σ</td>
<td>2.47</td>
<td>2.71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assessment of Performance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>µ</td>
<td>7.36</td>
<td>7.83</td>
<td>0.47</td>
<td>0.31</td>
</tr>
<tr>
<td>σ</td>
<td>1.36</td>
<td>1.70</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Observations**

In addition to the survey results, assessment results, and test scores, the subjects were observed as they completed the navigation training, supplemental training, and assessment tasks, and the observations were recorded. Each subject’s progress through the assessment was recorded, including paths taken, quality of area surveys, and strategies used. This data was helpful in the analysis of performance and radiation awareness beyond what the test results and numerical data showed. The observations recorded for each subject were transcribed and appear in Appendix C.

The subjects made their way through the maze after a short orientation that included descriptions of the controls and instruction on the operation of the virtual survey meter. Times on the maze ranged from two minutes and fifty seconds to six minutes and twenty-eight seconds. Since the navigation speed was fixed to a normal “walking speed,” the only discriminators in completion time were the number of wrong turns the subjects took. The average completion time was just under four minutes. The vast majority of subjects completed the maze with no wrong turns. All subjects appeared comfortable with the navigation by the time they had completed the maze.

The supplemental training was completed by the subjects assigned to the CAVE group. The group completed the five activities in an average of fourteen minutes and fifteen seconds. As each activity was completed, the subjects were asked to summarize their findings in their own words. When they arrived at the correct conclusion for each concept, they were allowed to move to the next station. Most subjects completed the exercises with no questions, but subjects 12, 14, and 21 required more time to complete
the exercises, meaning it took them longer to understand the concepts presented since they were only cleared to perform the next activity after they displayed an understanding of the concept. Based on the observations, all subjects should have completed the activity-based training with similar levels of understanding.

The assessment activity performed in the virtual environment provided an excellent opportunity for the researcher to observe the subjects as they applied their understandings of radiation awareness in the virtual power plant. As the subjects completed the four tasks, they were observed from a control room, and their behaviors recorded. The methods the subjects used to complete the tasks were noted, and unique solutions or strategies were recorded. The use of low-dose areas to reread procedures or to communicate with the control room was noted, activities which also displayed radiation awareness. Additionally, as the subjects surveyed the virtual radiation environment, their technique was noted, especially if they performed 3-D surveys from head to toe. Locations and situations where subjects appeared to be having trouble were also documented. The observational data assisted the researcher in the interpretation of the numerical results from the assessment.

One example, subject 13, a 22 year-old female, scored a 0.67 in the cumulative radiation awareness score that was based on objective assessment performance and test score. She did not improve on the exam, earning a 61-percent in both the pre-test and the post-test. These two measures would suggest that she had low radiation awareness, however observing her performance in the assessment would suggest otherwise. The subject used the low-dose areas on at least three occasions to consult the study material, noted radiation hazards beyond what the task called for, and exhibited excellent
awareness of her environment. In the path selection task, she properly chose path “B”, but she also noted that others taking that path should stay as close to the far wall as possible to minimize their dose. She noted that if someone had to take path “A”, they should maximize their distance from the large tank at the far end of the room. Based on these observations, it was clear that she understood the concepts of radiation awareness, applying many of them on the assessment. This was a textbook demonstration of the need to include qualitative information when assessing the performance of human subjects, as using only RA score as her measure of understanding would clearly not explain her depth of knowledge or comprehension.

Because of situations like the one described above, it was clear that the radiation awareness score and test scores alone were insufficient to completely measure the depth of a subject’s radiation awareness. The addition of observational data provides insights into how a subject might perform in an actual radiation environment: Are they aware of their surroundings, do they perform tasks quickly and efficiently, and do they take care to avoid excessive radiation exposure?

**Discussion**

The experiment provided a number of opportunities to compare the performance of the two groups of subjects. Performances on the written tests were compared to assess final score as well as improvement. The completion time and radiation dose received during the assessment were compared for the two groups. Finally, the radiation
awareness score was standardized so the results of the two groups could be compared. These tests draw some distinctions between the performances of the two groups.

The written test scores between the pre-test and post-test were compared for the computer based training and the CAVE training group. The results of the comparison are shown in Table 12. The pre-test average for the CBT group was reduced by subject 10’s score of 0. The subject reported that he did not think he could answer any of the questions so he chose not to guess. If the score of 0 is removed from the data set, the corrected average for the CBT group on the pre-test would be 50.5 rather than 45.9, a nearly 5 point difference. Since subject 10’s post-test score of 77 was very close to the average, removing this data point would reduce the overall improvement of the group to approximately 25 points, creating a 6 point difference between the two scores. As it stands, the CAVE group in this sampling performed slightly better, although the difference is not statistically significant, as shown in the Table. This is expected since only the final question was geared towards the training in the virtual environment. The other questions primarily measured declarative knowledge and simple calculational skills. Paper tests as an assessment tool are typically geared towards the measurement of declarative knowledge rather than application or understanding of concepts. In this experiment, the pre-test and post-tests were used as a traditional assessment tool.

<table>
<thead>
<tr>
<th></th>
<th>CBT</th>
<th>CAVE</th>
<th>P (T-test)</th>
<th>d (Effect Size)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Test Average</td>
<td>45.9</td>
<td>46.9</td>
<td>0.92</td>
<td>0.04</td>
</tr>
<tr>
<td>Post-Test Average</td>
<td>75.2</td>
<td>78.2</td>
<td>0.65</td>
<td>0.20</td>
</tr>
<tr>
<td>Improvement</td>
<td>29.3</td>
<td>31.3</td>
<td>0.83</td>
<td>0.09</td>
</tr>
</tbody>
</table>
The dose and time data for the assessment activities have been plotted as histograms. The data appear to be similar in form to lognormal distributions, which are skewed. Lognormal distributions are typically characterized by an offset from zero and a scale factor. Fitting the data to a lognormal distribution makes sense because the tasks cannot be completed in zero time, and the person completing the task cannot do so without receiving some radiation dose. These threshold values would theoretically represent the minimum time and dose necessary to complete the task. In addition, skewness and kurtosis have been calculated for each quantity. Skewness measures the relative position of the mean in the data set, and kurtosis measures the peakedness of the data set. Skewness between -1 and 1 represents data that is fairly close to being described by a normal distribution. Skewness outside of the range would represent a data set that would not be accurately described by a normal distribution. A kurtosis of -1 to 1 would represent a data set that is normally distributed, while values outside of the range would mean the data set is not normally distributed. Additional trials would serve to fill in the distribution to improve the estimates of these quantities. The plots of the data appear below.

Figure 41 is a histogram of the radiation exposure received by participants of both groups as they completed the assessment activity. A lognormal fit has been overlaid on the data. The distribution is characterized by a locational offset of 0.61 and a scale of 0.68. Skewness was calculated to be 3.57, and kurtosis was calculated to be 14.15. The median of the data set was 1.59. It does not appear that the data is normally distributed
based on these values, so use of the T-test for gauging statistical differences in the means is not appropriate.

![Graph showing radiation exposure for all experiment participants.](image)

**Figure 41:** Radiation Exposure for All Experiment Participants

Figure 42 shows a similar plot of radiation exposure received as the CBT group completed the assessment activity in the virtual power plant. Again a lognormal distribution was fit to the data. The distribution was characterized by a locational offset of 0.84 and a scale of 0.8. Skewness was calculated to be 2.57, and kurtosis was calculated to be 6.89, which show the data set is not normally distributed. The median of the data set was 1.55. Again, the large skewness and kurtosis show that the data is probably not normally distributed.
Figure 42: Dose Received During Assessment Activity for CBT Group

Figure 43 shows the result of fitting a lognormal distribution to the dose received by the CAVE group during the assessment activity. This distribution had an offset of 0.41 and a scale of 0.5. Skewness was calculated to be 1.53, and kurtosis was calculated to be 3.28, again showing the data set was not normally distributed. The median of the data set was 1.61.
Figure 43: Dose Received During Assessment Activity for the CAVE Group

Figure 44 is a histogram showing the completion time for the CAVE training. A lognormal distribution has been fit to the data. Skewness was calculated to be 1.42, and kurtosis was calculated to be 1.76, meaning the data is probably not normally distributed. The median of the data set was 443.
A histogram of the assessment activity completion time for the computer based training group is shown in Figure 45. Again, a lognormal distribution was fit to the data. Skewness was calculated to be 0.96, and kurtosis was calculated to be -0.83. These results show the data could be normally distributed, but they are quite close to the thresholds of +1 skewness and -1 kurtosis. The median of the data set was 440. Visually, the data appears to have a positive skew so assuming a normal distribution in this case would probably be incorrect.

Figure 44: Completion Time Histogram for CAVE Training
To better analyze the results of the assessment, the results of each factor of the radiation score were standardized. These results were combined to create a standardized radiation awareness score. Figure 46 shows a histogram of the standardized radiation awareness score for all participants with a normal distribution fit to the data. The data appears to have the classic shape of the normal distribution.

Figure 45: Completion Time Histogram for Computer-based Training
Figure 47 shows the standardized results for the twelve radiation awareness scores for the CAVE training group. A normal distribution has been overlaid on the histogram of raw data. The mean of the data set is 0.325, and the standard deviation is 2.114.
Figure 47: Standardized Radiation Score for CAVE Group

Figure 48 depicts the standardized radiation score for the Computer Based Training group. The histogram shows a mean of -0.35 and a standard deviation of 2.047. With the dataset of only 11 subjects, the data appears to approximate a normal distribution fairly well.
The standardized radiation awareness scores for each group appear to be normally distributed. Again additional data would help to further characterize the distributions. The results of the CBT and CAVE data sets can be compared.

Table 13 presents the statistical results for the comparison of the standardized radiation awareness scores. Two statistical tests were used to assess the differences between the two groups, Student’s T-test and Cohen’s Effect Size. The basic statistics such as mean and standard deviation are shown, as well as the results of Student’s T-test and Cohen’s Effect Size.

Figure 48: Standardized Radiation Score for CBT Group
Student’s T-test is used to assess statistical difference between the means of two data sets. The test involves dividing the difference in the means of two data sets by the difference in the standard error of the data sets. The most common interpretation of the T-test sets a significance threshold (p) of 0.05, although some have proposed the use of 0.2 (significant), and 0.3 (moderately significant) for small sample sizes (Winer, 1971). The p-value calculated using the T-test was 0.442, and the most common interpretations of a p-value of this magnitude would be that the test yielded results that were not significant.

Cohen’s d is a measurement of effect size, a quantity describing the magnitude of a treatment effect, which in this case is the effect of the CAVE training. Cohen describes an interpretive scale where 0.2 represents a small effect, 0.5 represents a medium effect, and 0.8 represents a large effect (Cohen, 1988). These two tests were used to assess the hypothesis that hands-on training in the CAVE virtual environment would result in increased radiation awareness. According to the effect size measurement, the CAVE

<table>
<thead>
<tr>
<th>Training Type</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAVE</td>
<td>12</td>
<td>0.33</td>
<td>2.11</td>
<td>0.61</td>
</tr>
<tr>
<td>CBT</td>
<td>11</td>
<td>-0.36</td>
<td>2.05</td>
<td>0.62</td>
</tr>
</tbody>
</table>

T-Test:
P-Value = 0.44
Effect Size:
Cohen’s d=0.33

Table 13: Statistical Results for Comparison of RA Scores
training had between a small and medium effect on radiation awareness score based on the calculated effect size of 0.33.

Using the guidelines discussed above, the statistical hypothesis tests yielded mixed results. However, additional evidence collected during observations of the assessment activity supports the interpretation of the effect size - that there was a small to medium improvement in radiation awareness resulting from the virtual reality training. The CAVE group appeared to perform slightly better in the assessment activity. The CAVE group showed slightly more improvement on the written exam, as well.

The observations recorded during the experiment, which have been transcribed in Appendix C, support the conclusion that learning did take place. Learning was described as “a relatively enduring change in observable behavior that occurs as a result of experience” (Eggen & Kauchak, 2001, p. 214) in chapter 2. In this case, the subjects experienced the training exercise in the virtual environment and the computer-based training. Although their performance on the first task was scored poorly, the subjects who received the radiation awareness training were more sensitive to receiving radiation exposure. More of the subjects in that group noted hazards in the environment, and many exhibited changes in behavior such as walking close to the wall to stay away from sources or noting that a worker should stay low to reduce their exposure. This information does not appear in the raw score, but it speaks volumes about the benefits of activity-based training.
Analysis

The quantitative measures developed for this experiment were designed to accurately measure a subject’s radiation awareness, but it became clear that the quantitative results alone were not sufficient to completely assess a subject’s performance. The qualitative information recorded during the experiment was essential to interpreting the experimental results. The performance of the CAVE group relative to the CBT group is dissected further below.

A comparison between the pre-test and post-tests scores for both groups of subjects shows a significant improvement of approximately 30 points, which amounts to correctly answering an additional two questions. The small difference between the two groups shows that the hands-on training was not especially beneficial to the subjects’ performances on the written assessment. The hands-on training was designed to benefit the subject in the application of their knowledge in a “real-world” environment more than in the recitation of declarative knowledge that is typically measured on a written test. It was evident that the subjects that received the CAVE training performed better on the questions that involved understanding of space such as the final question on the test, which all of the CAVE group answered correctly while only eight of eleven of the CBT group answered correctly. The test scores showed that the computer based training was effective for stimulating learning of declarative knowledge, while the CAVE training provided knowledge that was useful in the application of the skills.

The assessment activity also provided interesting results. The activity was designed to be an authentic assessment, where the subjects were asked to put the concepts
they had learned into practice in an innocuous environment. A comparison of the scores showed no statistical difference in radiation awareness score, a quantitative measure of effectiveness that was calculated based on post-test score, assessment completion time, assessment radiation exposure efficiency, and scores from the completion of four activities. The group that received the CAVE training completed the four activities in the assessment an average of one-minute faster and received approximately half of the radiation exposure, making it appear that the activity-based training was effective. The first of the four activities performed in the virtual power plant was the only one where there was a distinct numerical difference in performance between the two groups.

The CAVE group performed poorly on the first task, which required the subjects to locate the highest radiation reading in a room that stored barrels. A number of the subjects from the CAVE group did not complete adequate surveys of the area, because they were trying to avoid receiving radiation exposure. For example, subject 11 reported that he saw the radiation level in the room increasing quickly and therefore did not want to enter the space. Subjects 13, 16, 17, 18, and 19 reported similar concerns, choosing to stay close to the wall as they surveyed the area. Because these six subjects did not approach the barrels, they did not properly identify the hot spot in the room. It would appear that they did exhibit increased radiation awareness, but had not yet developed the judgment necessary to effectively balance the competing priorities of task completion and radiation exposure management. In addition, the subjects were not trained in survey procedures, and they were not provided with completion criteria for the tasks. These omissions increased the uncertainty in the collected data.
In addition to the increased sensitivity to radiation exposure demonstrated on the first task, the CAVE subjects’ performances also differed on the second task. In this case, the subjects who received CAVE training exhibited a better awareness of hazards on the second task. Eight of 12 subjects in the CAVE group identified hazards around the work area on Task 2, while only 2 of 11 subjects in the CBT group identified hazards. Most of the subjects identified the barrels to the left of the work area as a radiation hazard to be avoided during the work. This demonstrates that the CAVE group had a better understanding of their surroundings thereby exhibiting the use of higher level thought processes and transfer of knowledge from the training to the practical.

The radiation awareness score provided a quantitative measure of the subjects’ overall performances on the assessments. While the quantitative results showed that the training in the CAVE had a small-to-medium effect, at best, the qualitative results showed the subjects in the CAVE group had higher radiation awareness. The radiation awareness score did not tell the whole story about a subject’s performance. While the score depended on the performance on multiple tasks, there was only a distinction in the performance on one of the tasks. It appeared that the group receiving the CAVE training performed poorly, although they successfully avoided radiation exposure. The training seemed to increase their sensitivity to radiation exposure. In avoiding radiation, they failed to find the location of the radiation source in the space.

One of the key concepts that the training needs to convey is that there must be a balance between radiation exposure and the completion of tasks. The fifth question of the post-test was designed to highlight this concept - that sometimes traversing a high-dose area can reduce overall exposure if it can be done quickly. The learner needs to
understand what the numbers mean, how radiation exposure accumulates, and how to minimize their exposure. These are the kinds of skills that are gained from experience since they require a deeper understanding, and these are the kinds of skills that are effectively transferred from activity-based training.

Based on the test scores, assessment activity scores, and observations, it is clear that learning in the virtual environment did take place, although the quantitative effects of the training were small. Qualitative information such as the observations provided meaningful insight into the level of understanding possessed by the subjects. Using the correct terminology as they completed the assessment activity was evidence that they had internalized the information presented in the computer-based training, but the CAVE training would most likely manifest itself as behavioral changes in the field. These behavioral changes were evident on the first task, where at least half of the subjects did not approach the radiation source in the barrel. These subjects exhibited radiation awareness, but had not yet internalized what a significant radiation level was. They successfully avoided radiation exposure at the expense of completing the task satisfactorily, and they completed the tasks more quickly, understanding that time was an important factor of radiation dose avoidance. The subjects exhibited increased sensitivity to radiation by avoiding the sources and working quickly. These concepts were covered by the training, so improvement in those areas shows that the training is potentially effective. Additional trials are needed to solidify the quantitative results, however.

Since survey techniques and task completion were not trained, it is not surprising that there was a large variation in the subjects’ interpretations of the task instructions, which resulted in disparities in their performances. It is possible that adding a survey
activity to the training and solidifying the portions of the procedure that were open to interpretation would result in more consistent performance.

Conclusions

The experiment described in this chapter was designed to examine the change in radiation awareness demonstrated between subjects who received computer based training and those that received computer based training supplemented with activity-based training in an immersive virtual environment. The experiment was primarily quantitative, using surveys, quizzes, and a practical application in a virtual power plant to evaluate radiation awareness. Observations which aided the researcher in a deeper understanding of the training results were also gathered and appear as supporting evidence of findings.

A number of changes were made to the experiment following the initial pilot study. The supplemental training activity was redesigned to use more constructivist concepts, a major theory upon which these research questions rested, by creating a 5-station virtual training exercise. A software update, which increased the capabilities of the radiation dose model, was implemented, while the marker capability used in the original pilot study to locate source was no longer available. Collision detection, a feature that was requested by numerous participants in the pilot study, was added to prevent the subjects from walking through walls, making navigation more natural. These changes appeared to considerably improve the design quality of the experiment.
Eleven participants completed only the computer-based training, while twelve participants completed the computer-based training supplemented with the activities in the virtual environment. All participants entered the experimental trials with no previous radiation awareness training, which allowed the research to assess whether or not learning was actually a result of the training provided. After spending approximately an hour and twenty minutes studying the computer-based training material, the CBT-only group entered the assessment phase, completing tasks in the virtual power plant. The CAVE group received approximately fifteen minutes of additional, hands-on training based on constructivist principles in the virtual environment prior to completing the assessment.

The practical test consisted of four tasks that the subjects had to complete in the virtual radiation environment, which involved location of sources and the selection of paths and work locations. The subjects’ performances were assessed based on successful completion of the tasks, the radiation exposure received during the activities, the time required to complete the activities, and their performance on a post-test. Based on the statistical analysis of these quantitative measures, the data was statistically inconclusive for most measures, primarily due to the small sample size.

However, in addition to the quantitative measures described above, qualitative observations and participant feedback were collected. The qualitative observations showed that the group that completed the supplemental training exhibited traits that were indicative of radiation awareness, though not necessarily reflected in their RA scores. These traits included adjusting their paths to reduce radiation exposure, verbal noting of radiation sources and other hazards while in the environment, and performing 3-D surveys which CBT group members did not. The quantitative data collected during the
experiment slightly favored the group that performed supplemental training in the CAVE. The CAVE group performed the activity an average of one-minute faster, while receiving significantly less radiation exposure. Yet when these results were combined with the performance on the four tasks, the difference in performance was not particularly pronounced. Future experiments could be improved by recording and coding these qualitative results into a form that is more useful for comparison.

The original hypothesis of this research was that radiation awareness is higher in workers that have received hands-on training in a full-scale virtual mockup than those trained using traditional methods such as computer-based training, but the statistical results of the data collected during the experiment do not necessarily support this claim. However, the relatively small groups of subjects used in this experiment made drawing meaningful conclusions from the statistics difficult. The T-tests did not show significant differences between the radiation awareness scores of the CBT group and the CAVE group. However, it is important to note that based on the effect size calculation showing that the supplemental training provided a small to medium effect, additional trials would be needed to confirm the statistical results one way or the other. The most telling results were the significant reduction in radiation exposure exhibited by the subjects that had received the supplemental training, since the radiation awareness score combines quantities that could be affected by concepts that were not trained. While the quantitative results provided some information about performance, the observations collected by the research as the subjects performed the assessment suggest that their behavior was modified as a result of the additional training, and, therefore, learning took place.
Chapter 8

Conclusions and Recommendations for Future Work

Immersive virtual reality provides an environment where many things are possible. Past work has shown its utility in areas such as facility design and construction, as well as training in other industries. Because of this, it was desirable to assess the technology’s suitability for nuclear industry training given the importance placed on performance improvement. The VR technology has many features that make it suitable for training including the ability to create context for the task being trained, the ability to add simulation models to the geometry, repeatability, a natural interface and interaction, and its ability to generate interest in the learner due to the novel training environment.

Learning theories such as constructivism, discovery learning, and experiential education support the use of immersive virtual reality because they stress the value of enabling the learner to actively experience concepts rather than just passively taking them in. Additionally, the theory of multiple intelligences holds that people can learn best by many different methods, and therefore, different training practices are required to reach all of these different learners. People learn more effectively when the training environment is similar to the environment where the concept will be applied, demonstrating the importance of matching the training to the task. Activities and procedures are not best taught in the classroom; rather they are more effectively learned in the field. When it is not possible to train in the field, virtual reality is a potential substitute because of its ability to present visually accurate environments while
simulating additional data such as radiation, smoke, fire, or other hazards, providing a strong sense of physical and psychological similarity.

Discovery learning and experiential education suggest that knowledge is best transferred when the learner is able to take what is already known and extend that understanding to fit new information or experiences to which they are exposed. Virtual reality provides an environment where this is possible. In a virtual world, a learner can experience first-hand environments and situations that cannot be experienced using a conventional training environment such as on a computer screen or in the actual environment because it is too dangerous to perform. On-the-job training is a valuable resource, but the training varies depending on the experience of the mentor, whereas VR provides an environment where training can be vetted, controlled, supervised, and repeated until the learner has internalized the information. This is important to error-free performance, which is the ultimate goal of training.

Radiation awareness was chosen as the concept to be trained in this experiment because it represents a hybrid of a number of concepts. It blurs the distinction between training and education because it can be immediately applied, as training is, but it also seeks to teach long-term, deeper understanding of radiation exposure and dose avoidance. Radiation awareness depends on an understanding of fundamental concepts of radiation, but it also depends on experience in working in radiation environments, which is ultimately the most important concept to understand. For these reasons, a two-pronged approach to assessment of radiation awareness was selected. This approach used an examination to test declarative knowledge about radiation and dose, as well as a practical
environment that tested the transfer of knowledge and the learner’s application of the concept in the field.

The exercise was intended to use constructivism and discovery learning practices applied to conceptual training in an immersive virtual environment. Basic knowledge was provided by the computer-based training, and practical knowledge was instilled using the virtual environment. As both of these types of knowledge are necessary, both of these types of knowledge were assessed.

The training methods were designed to mimic those currently used in the nuclear industry. The majority of information is taught using computer based training, while some programs supplement the CBT with hands-on training using mockups or role-playing exercises. To mimic this, the pilot experiment compared the performance of the control group, taught using computer-based training only, with two groups that had performed activity based training using either a Teletrix simulated survey meter or the virtual environment. The Teletrix simulated meter is used by some utilities to provide hands-on training prior to performing activities in the plant. The virtual reality training environment was designed to fulfill a similar role, with the addition of all VR has to offer such as the ability to recreate areas of the plant that are inaccessible or the ability to accurately model radiation exposure.

An authentic assessment environment consisting of a notional power plant with multiple rooms and pieces of equipment was constructed to evaluate the subjects. The tasks on the assessment activity were intended to test the subjects’ understanding of the concepts surrounding ALARA and radiation dose reduction. The tasks required them to locate a hot spot by measuring the radiation level, select a work location by surveying an...
area and noting hazards, select a path used to traverse an area, and mark the suspected location of a radiation source. Each of these tasks required the subjects to find a balance between radiation exposure, completion time, and thoroughness. Radiation sources were mixed between waist level, high, and low to create three-dimensional gradients, with the intent of forcing the subjects to perform careful surveys of their surroundings. Subjects were forced to see their surroundings in three-dimensions; subjects who did not measure anything beyond what was in front of them at waist level did not receive high scores on the task completion component of the radiation awareness score. Subjects who earned high scores typically performed three-dimensional surveys and successfully balanced time, dose, and thoroughness.

The pilot experiment’s training activities were unsuccessful in creating a measurable difference in the radiation awareness of the test subjects as measured by their radiation awareness score, which was calculated from a combination of post-test score, efficiency, radiation exposure, and the successful completion of four tasks. The majority of the pilot experiment subjects were nuclear engineering students who had already received various levels of radiation awareness training. Because of this, it was difficult to measure their knowledge before and after the training. Most scored quite well on the examination, and the pre-test to post-test difference in scores was small, suggesting that their declarative knowledge had plateaued prior to receiving the training. Many subjects appeared to have difficulty with the practical test, which hinted at the disconnect between knowing a theory and applying it. This confirmed that measuring knowledge with tests and examinations did not accurately predict performance in the field, where one could argue that application is more important.
Changes made to the experiment and training activities resulted in a larger distinction between the radiation awareness of the control group and the group of interest, which received training in the virtual environment. An activity-based training environment, designed with constructivist principles in mind, was created to enable learners to solidify and build upon the knowledge they had gained via the computer-based training. The training was intended to stimulate understanding of the behavior of radiation in a plant-like environment so that the knowledge could be applied in the practical sense.

The final experiment was designed to compare the radiation awareness of those who had received computer-based training with those who had received computer-based training supplemented by activity-based training. Since the Teletrix meter was not available, and the pilot showed no discernible difference in performance between the Teletrix group and the others, it was not used for the final experiment. The experiment was run in a manner similar to the pilot experiment where subjects completed a pre-test to gauge their knowledge prior to completing any training, then completed computer-based training and supplemental training (for the CAVE group), and finally performed the practical assessment in the virtual environment and completed the post-test to gauge their end knowledge. Again, the subjects’ radiation awareness was measured using the radiation awareness score calculated from the post-test score, efficiency score (dose/time), completion time, and scores on the four tasks. In addition to the radiation awareness score, however, observational data was collected which helped complete the interpretation of the data.
The raw scores on the final experiment slightly favored the group that had received the supplemental training. They received approximately fifty-percent less radiation exposure and finished on average one-minute faster. While the dose difference was not statistically significant, the effect size suggests that the CAVE training had a moderate effect on performance (d=0.58). The completion time was not significantly different between the two groups, but the effect size suggested that the CAVE training had a small to medium effect (d=0.32). These two components showed that the CAVE training was effective in increasing the efficiency of the performance of the subjects in the radiation environment, and the training helped them to learn to avoid radiation exposure. These quantities would suggest that the training was successful, and that subjects that received the radiation awareness training in the virtual environment indeed had higher radiation awareness.

While this group performed well on the time and dose measures, much of the CAVE group failed to complete the first task on the assessment. It appeared that their failure was not driven by carelessness as much as over-sensitivity to radiation exposure. The average radiation level in the room was about 5 mR/hr, a fairly low radiation level. Many of the subjects in the CAVE group commented that they did not want to enter the environment as they watched the radiation levels increase. In this case, the training was successful in teaching the subjects to avoid dose, but they had not yet learned to balance the importance of completing the tasks with dose avoidance. Also, it was clear that they had not yet gained sufficient experience to understand the difference between a radiation level of 5 mR/hr compared to 50 mR/hr. In this respect, the training was insufficient.
It should be noted that the subjects that received the radiation awareness training in the CAVE exhibited a heightened sensitivity to radiation, which is clearly evident from their performance on the first task as well as the lower radiation exposure. Subjects were trained on avoidance of radiation exposure; however, they were not trained on task completion or surveying techniques. This possibly explains some of the variation in the subjects’ performances. Training in those concepts would enrich the overall training, as well as decrease the variation of the performance.

While the statistical results for the experiment were mixed with the time and dose showing that the CAVE training was effective and the completion of the first task on the assessment showing otherwise, observational data was used to clarify the results and resolve the disagreement. While performing the activities, the subjects’ actions were noted and additional information was recorded. The subjects who had completed the supplemental training in the CAVE exhibited superior awareness of their surroundings and appeared to better apply the principles of radiation awareness. They identified more hazards on the second task of the assessment and exhibited a better spatial understanding of dose avoidance such as adjusting their path to reduce their dose on the third task. These additional pieces of data show that the training was effective in generating increased awareness of the radiation in the plant environment.

This experiment required the development of technology, the construction of a number of virtual environments, synthesis of a training program, and development of assessment techniques. Because each of these components was new or novel, it is difficult to gage the contribution of each to the outcome of the experiment. The CAVE technology has evolved significantly since its introduction in 1992 to the point where it is
now able to be used commercially rather than simply for research. The software available to run the CAVE and similar displays is constantly improving in its ability to create more and more realistic environments. It was clear that when the work detailed in this dissertation began in 2002, the technology was not quite ready for these kinds of applications. The software changes in the months between the pilot and the final experiment that prevented subjects from walking through the walls is a perfect example of one of these advances that greatly improve the utility of the virtual environment. The computer based training programs were selected to be representative of those currently in use although they did not use many of the advanced multi-media that some training applications now feature. Different training materials could be more or less effective.

The assessment techniques were designed to address the shortfalls of current assessments, which rely primarily on tests of knowledge rather than knowledge and skills. The tests were intended to evaluate knowledge of simple concepts, simple calculations, and understanding of spatial concepts. The assessment here provided an opportunity for the subjects to transition from theory to practice and apply in a real situation the skills they should have learned through the training.

After observing the performance of the subjects in the assessment, a number of improvements or revisions could be made in the future to the training activity in the virtual environment. This training environment was developed with the systems approach to training in mind, so following the ADDIE process, the feedback from the training can be used to improve the next round of training. Training could potentially be improved by including an activity, which teaches techniques in surveying in three-dimensions. The training activity demonstrated the three-dimensional nature of radiation,
but it did not effectively train the learner to perform a 3-D survey. Further, an activity designed specifically to give the subjects an understanding of the magnitudes of numbers rather than just the “shape of the curve” would also be beneficial such that they could tell the difference between the 5 mrem and 15 mrem for the same task. Based on their performance on the first task, it was clear that many of the subjects were too sensitive to radiation exposure since they did not want to enter a radiation field that many measured to be between 5 and 10 mR/hr, which in their minds represented too high a risk. An exercise that provided them with an understanding of the magnitude of a radiation source would be helpful in conquering this fear.

The CAVE training successfully transferred the information to the learner, and the hybrid theoretical-practical training enabled groups of subjects who had no prior knowledge of radiation to effectively learn and apply the principles of radiation awareness in a simulated radiation environment. Based on the performance of the CAVE group, the supplemental training activity could still be improved, but this experiment demonstrates that the systematic approach to training and the ADDIE process can and should be applied to this type of training program. Given the number of engineers that will need to be trained well and quickly in the very near future and the relative success of this research, the nuclear industry should seriously consider adding VR applications to the training models used in the industry today.
Future Work

A number of activities could be performed to improve and extend the research detailed in this dissertation:

1. The dose model could be improved to support input from shielding codes or dose prediction and management programs. This would enable the effects of shielding to be modeled, creating a more useful training environment, since all of the components of ALARA – Time, Distance, and shielding – could be simulated and taught.

2. Transfer of training and knowledge retention could be assessed to determine if the CAVE group achieved a deeper understanding of the concepts. This would involve re-testing the subjects after a period of time and comparing the results. If the “deeper learning” has been achieved via the training, the subjects who received the additional VR training should outperform those that have not on subsequent applications of knowledge and skill.

3. Because the expense of the full-scale multi-wall CAVE may preclude its use as a training environment, it would be interesting to perform the experiments detailed in this dissertation using a large-format, single-wall display rather than a CAVE. Research has shown that field of view and sense of immersion do affect performance, but if similar learning can be achieved on a lower-cost footprint, the chances of VR training being adopted will increase greatly.
4. The VR training environment should be tested in an operational utility environment via a pilot test in production environment. Operational testing using plant personnel would show whether or not the VR training is worthwhile, and it would assist in the transition from the research environment to a production environment.

5. Previous research has suggested that certain types of subjects excel in the virtual environment. In the research detailed in this dissertation, there were clear differences in the spatial abilities of some of the subjects based on their performance on the maze training task, their approach to planning of the four-task assessment, and the amount of time it took them to grasp the concepts during the supplemental training. Perhaps deeper psychological testing and spatial aptitude tests would help to identify the types of people who would excel in VR training. If it can be shown that those are the same types of personnel found working in a plant environment, it would provide additional support for the use of VR training in the nuclear industry.

6. Additional trials of the experiment should be performed. Additional subjects would resolve the uncertainty in the statistics, enabling stronger conclusions to be drawn from the data. Also, using more subjects, the training could be optimized and streamlined to support the large numbers of people that would receive the training in a nuclear power plant’s maintenance outage preparations.
Contributions

The principal contributions of this research are the development and testing of activity-based supplemental training, development of a realistic radiation overlay model, and the development of an authentic assessment where learning was tested in a plant-like environment. Much of the previous work in virtual reality described in the literature has centered on small-scale tasks. In contrast, this research was intended to test the implementation of immersive virtual reality in a form that could be used in a training program today. Computer based training consisting of a PowerPoint presentation and a PDF manual was supplemented with activity based training in a virtual environment. The multi-station training scenario provided a constructivist environment where the learner could experiment with demonstrations showing various concepts related to dose-reduction. To make the training more realistic, a physics-based radiation modeling simulation was developed to allow the trainee to measure radiation environments with a simulated survey meter. This was designed to produce a more interactive experience to engage the learner further. The experiment was designed to measure learning using traditional methods as well as with new methods including a hands-on “authentic” assessment. The assessment took place in a notional power plant, and it forced subjects to apply what they had learned in training. When the subjects were assessed in the virtual environment, they had the opportunity to make mistakes in an innocuous environment, where a trainer could coach or correct incorrect behavior, safely. Finally, the work presented in this dissertation has provided meaningful data that can be used for future comparisons of training methods.
Works Cited


Appendix A

Radiation Dose Model

The radiation dose model is used to simulate worker dose and radiation field in the virtual environment dynamically, in real-time. The input and calculations are described in the following sections.

Input:

The input to the dose model is currently read from a VegaPrime panel that allows the radiation model to is loaded in the virtual environment at the same time as the geometry. The input contains a few parameters for each source. The source strength in Becquerels and the energy of the emitted photons in MeV are read from a blocks in the panel. The sources are given a location by attaching them to objects or transforms, which are simply positions in space. Any number of radiation sources can be created. Figure 49 shows the panel in the VegaPrime Graphical User Interface (GUI) for inputting a radiation source.
The Geiger Tool can be attached to the Wand device so that it can be operated in a manner similar to an actual survey meter. Inputs on the panel include the graphical object that represents the detector and the text readout. The panel also allows the meter to act like a dosimeter by accumulating radiation dose when the “setAccumulate” checkbox is selected.
The detector and the sources are combined to create realistic radiation overlays for the virtual mockups, which can be interrogated using the virtual survey meter. The calculation procedure used is described in the next section.
**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 0. 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 51.
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. Eq. 1 shows the equation for the flux at point r.

\[ \phi(r) = \frac{S}{4\pi r^2} \cdot e^{-\mu r} \]  

where:

- \( S \) = source strength in Becquerels (dps or tps)
- \( r \) = distance from source in centimeters
- \( \mu \) = attenuation coefficient in material (cm\(^{-1}\))

**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, as depicted in Eq. 2. 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.

\[ X \left[ \frac{mR}{hr} \right] = 0.0657 \cdot \phi \cdot E \cdot \left( \frac{\mu}{\rho} \right)_{air} \]
where:

\[ \phi = \text{flux in photons/cm}^2\text{-s} \]

\[ E = \text{Energy in MeV} \]

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

**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 Eq. 3. The coefficient represents the unit conversion from Roentgens to rads.

\[
D \left[ \frac{\text{mrad}}{\text{hr}} \right] = 0.875 \left( \frac{\mu}{\rho} \right)_{\text{tissue}} \times \phi
\]

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.
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, which is simplified in Eq. 4.

\[
X \left[ \frac{R}{hr} \right] = \frac{\phi \left[ \frac{\text{photons}}{\text{cm}^2 \cdot \text{s}} \right] \cdot E \left[ \frac{\text{MeV}}{\text{photon}} \right] \cdot 1.602 \times 10^{-11} \cdot \frac{J}{\text{MeV}} \cdot \frac{3600}{\text{s}} \cdot \frac{s}{\text{hr}} \cdot \frac{34 \text{ kg}}{\text{C}} \cdot \frac{1000 \text{g}}{\text{kg}} \cdot \frac{3881}{\text{R}}}{34 \text{ kg}}
\]

\[ \text{Eq. 4} \]

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\times10^{-4} \text{ Coulombs} of charge results in the conversion factor, shown in Eq. 5 and Eq. 6.

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

\[
1 \text{ R} = \frac{2.58 \times 10^{-4} \text{ C}}{1 \text{ kg}} \cdot \frac{1 \text{ ion pair}}{1.60 \times 10^{-19} \text{ C}} \cdot \frac{34 \text{ eV}}{1 \text{ ion pair (in air)}} = 5.47 \times 10^7 \text{ eV/kg} = 5.47 \times 10^7 \text{ MeV/g}
\]

\[ \text{Eq. 5} \]

\[
1 \text{ R} = \frac{5.47 \times 10^7 \text{ MeV/g}}{1.60 \times 10^{-6} \text{ eV/Mev}} = 87.5 \frac{\text{erg}}{\text{g (air)}}
\]

\[ \text{Eq. 6} \]
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.

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 (Eq. 7)

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

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 shown in Eq. 8.
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 52 shows the measured NBS mass-energy absorption coefficient and the function fit to that data used in the dose model calculation.

\[
\mu_{\text{air}} = 2.774191 \times 10^{-6} E^4 - 8.508536 \times 10^{-5} E^3 + 1.033186 \times 10^{-3} E^2 - 6.370574 \times 10^{-3} E + 3.303224 \times 10^{-2}
\]

Figure 52: Comparison of Measured and Calculated Mass-Energy Absorption Coefficient for Air
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 (Eq. 9) appears below.

\[
\mu_{\text{tissue}} = 4.251514 \times 10^{-3}E^6 - 2.094159 \times 10^{-2}E^5 + 2.935603 \times 10^{-3}E^4 + 8.518912 \times 10^{-1}E^3 - 5.411368 \times 10^{-2}E^2 + 3.931925 \times 10^{-2}E + 2.360246 \times 10^{-2}
\]

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

The expression for the second region (Eq. 10) appears below:

\[
\mu_{\text{tissue}} = 8.38606 \times 10^{-6}E^4 - 2.25563 \times 10^{-4}E^3 + 2.26668 \times 10^{-3}E^2 - 1.08867 \times 10^{-2}E + 3.99109 \times 10^{-2}
\]

The use of this function results in errors of 1-percent or less for the entire energy range.

Figure 53 shows a plot of the NBS data and the functional fit of the data used in the dose modeling program.
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 (Eq. 11).

\[ \mu_{\text{air}} = 7.692385 \times 10^{-5} E^{-0.4530147} \]
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 54.

![Mass Attenuation Coefficient - Air vs Energy (MeV)](image)

Figure 54: Attenuation Coefficient for Air

**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.

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

The laboratory experiment was performed on a rig that is generally used for calibration of hand-held survey meters. The rig holds 2 Cesium-137 sources (70 milli-Curie and 46 Curie) protected by a shield. A track extends 3 meters from the source shield. The track holds a small cart attached to a digital measuring tape. Detectors can be attached to the cart, and their dose versus distance characteristics can be evaluated. The setup is shown in Figure 55.
Two sets of experiments were performed. Two detectors, an electronic dosimeter and a survey meter, were mounted on the moveable cart. Starting at contact with the source shield, the dose rate and total dose received were recorded for each location at 0.5 meter increments. The detectors were exposed for two minutes at each location.

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

Figure 56 and Figure 57 display the measured and calculated dose rate and the error between the two measurements, respectively, for a small (70 milliCurie) Cesium-137 source. The dose model overestimates the dose rate by a large amount when the detector is close to the source, and the error decreases as the distance increases. The overestimation of the dose rate makes the model conservative, although determining the source of the error and reducing the error require further study. Possible sources of error are the geometry of the source, error in the procedure, detector efficiency, and error in the measurement of the source strength.

![Dose Rate vs Distance (70 mCi Cs-137)](image)

Figure 56: Measured and Calculated Data for Radiation Dose Model with Small Cs-137 Source
Figure 58 and Figure 59 display the measured and calculated dose rate and the error between the measurements of dose rate and cumulative dose, respectively, for a large (46 Curie) Cesium-137 source. Again, the dose model overestimates the radiation dose and the cumulative dose. The error appears to be a smaller percentage using the larger source, possibly due to the higher count rate. The dose model functions similar to an ideal detector so errors in detector efficiency and source geometry may account for the error in the measurement; however, additional study is needed.

Figure 57: Error in Measurement for Small Cs-137 Source
Figure 58: Measured and Calculated Dose Rate for Large Cs-137 Source

Figure 59: Error in Measurement for Large Cs-137 Source
The radiation dose model was tested using only a Cesium-137 source. Additional sources with multiple gamma-ray energies such as Cobalt-60 should be tested. In its present form, the dose model provides information on the radiation field and the total dose accumulated. The model does not, presently, account for shielding, although this upgrade is planned in the near future.
Appendix B

Pilot Experiment Materials

This appendix contains all of the materials used in the experiment such as quizzes, surveys, worksheets, and role playing exercises. First, the pre-experiment survey, which collects information about the subject, is presented. Next, the pre-and post-experiment quizzes are presented. Fourth, the data collection worksheet for the supplemental time and distance activities is included. The assessment activity scenario, overhead plant diagram, and dose map are shown. Finally, the post-experiment survey, which asks for the subjects’ thoughts on the training they received and their feelings on the virtual reality application, is documented.

Appendix B Documents:

1. Pre-experiment Survey
2. Pre-experiment Quiz
3. Post-experiment Quiz
4. Data Collection Worksheet
5. Reading Exercises for Time-Dose Experiment
6. Assessment Activity Scenario, Plant Diagram, and Dose Map
7. Post Experiment Survey
Pre-experiment Survey

Subject Number: ______________
Age: ______________
Occupation: _______________________________________
How long have you been in your current position (semester standing if student)? ____________
Do you or have you ever had unescorted access to a nuclear power plant or Penn State’s Reactor?
YES ___________ NO ___________
If yes, how long ago was your last Radiation Awareness (re)training? ______________
How do you feel you learn best?
1. Reading books or procedures
2. Watching demonstrations
3. Hands on activities
4. Classroom Instruction (Lectures)
5. Computer-based/Web-based Training
6. Other (specify) ___________________________________________
Have you ever visited Penn State’s CAVE or a similar visualization facility?
YES ___________ NO ___________
On a scale of 1-10, one being not comfortable at all and 10 being completely comfortable, how comfortable are you with technology?
1 -- 2 -- 3 -- 4 -- 5 -- 6 -- 7 -- 8 -- 9 -- 10
On a scale of 1-10, one being not a computer user and 10 being a power user, how comfortable are you with using a computer?
1 -- 2 -- 3 -- 4 -- 5 -- 6 -- 7 -- 8 -- 9 -- 10
**Pre-Experiment Quiz:**

1) What does the acronym ALARA stand for?  
[As Low As Reasonably Achievable]

2) What are the three components of ALARA?  
[Time, Distance, and Shielding]

3) If a source is measured to be 10 mR/hr at 1 foot, approximately what will the survey meter read at a distance of 2 feet?  
[2.5 mR/hr]

4) If you double your distance between you and a source, how much will your dose decrease?  
[a factor of 4]

5) If you stand in a room with a radiation field of 10 mR/hr for 12 minutes, about how much radiation have you received (in mrem)?  
[2 mrem]

6) Which path has the lowest radiation dose?  

[A, farthest from all high-dose sources or B, most direct route]
Post-Experiment Quiz:

1) What does the acronym ALARA stand for?
[As Low As Reasonably Achievable]

2) What are the three components of ALARA?
[Time, Distance, and Shielding]

3) If you are standing 3 feet from a source, and you want to cut your dose in half, about how far away do you need to move?
[SQRT(18) ~4.25 feet]

4) If you are doing a job in a radiation field of 60 mR/hr, and it takes you 20 minutes to complete the job, assuming the radiation is predominantly from gamma-emitters, about how much radiation have you received (in mrem)?
[20 mrem]

5) You have to choose between two paths to enter an area. One path has a radiation field of 100 mR/hour and requires 5 minutes to traverse, while the second path has a radiation field of 40 mR/hr and requires 15 minutes to traverse. Which path would you take to minimize your radiation exposure?
[the first (8.3 mR for the first path, 10 mR for the second)]

6) Which path has the lowest radiation dose?

[B, farthest from all sources, most direct path]
Training Worksheet

Subject number: ____________

Distance:

To determine the effect of increasing distance between you and the source, measure the radiation field at each red ball by placing the meter at the designated location. Record the radiation readings below:

Location 1: _______________ mR/hr

Location 2: _______________ mR/hr

Location 3: _______________ mR/hr

Location 4: _______________ mR/hr

Location 5: _______________ mR/hr

Location 6: _______________ mR/hr

Time:

To determine the effect of exposure time on radiation dose, read the passage displayed in front of you while holding the survey meter. Record the dose rate and the time and calculate the dose you received

Passage 1: Dose Rate: _____ Time: ___ Dose: ________ mrem

Passage 2: Dose Rate: _____ Time: ___ Dose: ________ mrem
Reading Exercises:

Robert Frost’s “The Road Not Taken”

TWO roads diverged in a yellow wood,
And sorry I could not travel both
And be one traveler, long I stood
And looked down one as far as I could
To where it bent in the undergrowth;

Then took the other, as just as fair,
And having perhaps the better claim,
Because it was grassy and wanted wear;
Though as for that the passing there
Had worn them really about the same,

And both that morning equally lay
In leaves no step had trodden black.
Oh, I kept the first for another day!
Yet knowing how way leads on to way,
I doubted if I should ever come back.

I shall be telling this with a sigh
Somewhere ages and ages hence:
Two roads diverged in a wood, and I—
I took the one less traveled by,
And that has made all the difference.

Paragraph 2 of the U.S. Declaration of Independence

We hold these truths to be self-evident, that all men are created equal, that they
are endowed by their Creator with certain unalienable Rights, that among these are Life,
Liberty and the pursuit of Happiness.
That to secure these rights, Governments are instituted among Men, deriving their just powers from the consent of the governed, that whenever any Form of Government becomes destructive of these ends, it is the Right of the People to alter or to abolish it, and to institute new Government, laying its foundation on such principles and organizing its powers in such form, as to them shall seem most likely to effect their Safety and Happiness.

Prudence, indeed, will dictate that Governments long established should not be changed for light and transient causes; and accordingly all experience hath shown that mankind are more disposed to suffer, while evils are sufferable than to right themselves by abolishing the forms to which they are accustomed.

But when a long train of abuses and usurpations, pursuing invariably the same Object evinces a design to reduce them under absolute Despotism, it is their right, it is their duty, to throw off such Government, and to provide new Guards for their future security.

Such has been the patient sufferance of these Colonies; and such is now the necessity which constrains them to alter their former Systems of Government. The history of the present King of Great Britain is a history of repeated injuries and usurpations, all having in direct object the establishment of an absolute Tyranny over these States. To prove this, let Facts be submitted to a candid world.
Radiation Survey Activity:

You have been tasked with taking some radiation readings in a few areas of the Aux Building. The equipment is located in five rooms in the building. Familiarize yourself with the space using the attached figure and dose map. The areas were last surveyed late last week by Radiation Protection.

Recall that area radiation readings given in mR/hour are underlined, and hot spots are denoted by a bold HS. Also, radiation readings may be given for Head Level (HL), Waist Level (WL), and Knee Level (KL) if a strong gradient exists. If you require it, the low-dose waiting areas have been marked on the dose map (LOW DOSE).

Task 1:

The first room serves as a storage area for radwaste. Enter the room through the door and perform a thorough survey of the area around the barrels to find the maximum radiation level. Call the control room and report the radiation level. [>25 mR/h]

Task 2:

The second room contains an emergency diesel generator. The air filter on the diesel is slated to be changed next week. The filter can be accessed from two locations designated A and B on the figure on the next page. Enter the space and survey the potential work areas. Choose between the two potential work locations for this task to be performed and note any nearby hazards. [Option B]

Task 3:

Teams are scheduled to be working in the fifth area later this week. To navigate to the final work area, you can take two different paths. Survey each path carefully and recommend a path for the workers to safely pass through the area. One path, shown in red on the next page, traverses the third room, which contains four heat exchangers, two filtration units, and storage drums. The second path, shown in teal on the next page, traverses an area containing two heat exchangers, a storage tank, and storage drums. [path B, lower dose rates]

Task 4:

Some maintenance is expected to take place in the fifth room later this week. The fifth area contains three storage tanks and some drums. We’ve received some reports that there is a hot spot in the area that’s led to larger than expected exposures. Survey the area and locate the hot spot. Mark the hotspot with a marker (red button on the wand to switch tools and pull the trigger to mark). Upon completion of your survey, return to the entrance and notify the control room.

Hot Spot Position [2.967, -13.094, 2.761]
Post Experiment Survey:

Subject Number: _____________

Training Method (circle one):  CBT only    Teletrix    CAVE

1.) On a scale of 1-10, 1 being extremely difficult and 10 being simple, was it difficult to learn to use the virtual environment?
1    --    2    --    3    –    4    –    5    --    6    –    7    –    8    –    9   --   10

2.) On a scale of 1-10, 1 being more confused and 10 being fully understand, after the training how well do you think you understand the Time and Distance components of ALARA?
1    --    2    --    3    –    4    –    5    --    6    –    7    –    8    –    9   --   10

3.) On a scale of 1-10, 1 being not helpful and 10 being extremely helpful, was the practical exercise helpful to your radiation awareness?
1    --    2    --    3    –    4    –    5    --    6    –    7    –    8    –    9   --   10

4.) On a scale of 1-10, 1 being not helpful and 10 being extremely helpful, was the classroom instruction helpful to your radiation awareness?
1    --    2    --    3    –    4    –    5    --    6    –    7    –    8    –    9   --   10

5.) On a scale of 1-10, 1 being poorly and 10 being excellent, how well do you feel you performed on the final activity in the CAVE?
1    --    2    --    3    –    4    –    5    --    6    –    7    –    8    –    9   --   10

Comments:
Appendix C

Revised Experiment Materials and Raw Data

The materials used in the revised experiment are presented in this section, and the corresponding raw data collected for the experiment is presented in a series of tables in this section.

1. Supplemental Training Worksheet
2. Table 14: Training Time
3. Assessment Activity Materials
4. Table 15: Assessment Activity Data
5. Pre-experiment Survey
6. Table 16: Pre-experiment Survey Data
7. Pre-Test
8. Table 17: Pre-Test Results
9. Post-test
10. Table 18: Post-Test Results
11. Post-experiment survey
12. Table 19: Post-experiment Survey Data
13. Observations
Supplemental Training Worksheet:

Distance:
To determine the effect of increasing distance between you and the source, measure the radiation field at each red ball by placing the meter at the designated location. Record the radiation readings below:

Location 1: ___________ mR/hr  Summarize your observations:
Location 2: ___________ mR/hr
Location 3: ___________ mR/hr
Location 4: ___________ mR/hr
Location 5: ___________ mR/hr
Location 6: ___________ mR/hr

Time:
To determine the effect of exposure time on radiation dose, read the passage displayed in front of you while holding the survey meter. Record the dose rate and the time and calculate the dose you received

Passage 1:  Dose Rate: _______ Time: ___________ Dose: _________ mrem
Passage 2:  Dose Rate: _______ Time: ___________ Dose: _________ mrem

What did you observe?

Circle:
Starting with the outside circle walk around the radiation source in the center of the concentric circles. Note the radiation readings as you walk around it. Move in to the next circle. Walk around that one. Repeat until you reach the last circle/sphere. Run your meter over the sphere. What happens as you run the meter over the sphere? What is happening to the radiation level as you walk around the circle? What happens as you move closer to the source?

Moving Source:
Proceed to the next station with the moving barrel:
Stand in front of the “stand here” sign. Hold up the survey meter. What happens to the radiation level as the barrel moves toward you? Away from you?

Radiation Hunt:
Proceed to the final station with the equipment mockup:
Stand on the “Stand here” sign. With the meter search for the radiation source. Where would you stand if you had to watch the pressure gauge during a maintenance evolution? Why would you choose to stand there?
Training Time Raw Data:

Table 14: Training Time

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<th>training</th>
<th>maze time</th>
<th>study time</th>
<th>training time</th>
<th>total training</th>
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<td>1:10:00</td>
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Radiation Survey Activity:

You have been tasked with taking some radiation readings in a few areas of the Aux Building. Familiarize yourself with the space using the attached figure and dose map. The areas were last surveyed late last week by Radiation Protection.

Recall that area radiation readings given in mR/hour are underlined, and hot spots are denoted by a bold HS. Also, radiation readings may be given for Head Level (HL), Waist Level (WL), and Knee Level (KL) if a strong gradient exists. If you require them, the low-dose waiting areas have been marked on the dose map (LOW DOSE).

Task 1:
Enter room one, the storage area for radwaste, through the door and perform a thorough radiation survey using the meter of the area around the barrels to find the maximum radiation level. Call the control room and report the radiation level.

Task 2:
The air filter on the emergency diesel generator housed in room two is slated to be changed next week. The filter can be accessed from two locations designated A and B on the figure on the next page. Perform a radiation survey of the two potential work areas. Choose between the two potential work locations for this task to be performed and note any nearby hazards.

Task 3:
Teams are scheduled to be working in Room 5 later this week. To navigate to the work area in Room 5, you can take two different paths. One path, shown in red on the next page, traverses the third room, which contains four heat exchangers, two filtration units, and storage drums. The second path, shown in teal on the next page, traverses an area containing two heat exchangers, a storage tank, and storage drums. Perform a survey of each path and recommend a path for the workers to safely pass through the area.

Task 4:
Maintenance is scheduled to be performed in Room 5 later this week. The room contains three liquid holding tanks and drum storage. Dose records from personnel who have worked in the area have shown higher than expected exposures, recently. Survey the area and locate the hot spot. Report the relative location and the radiation level to the control room. Upon completion of your survey, return to the entrance remembering to minimize your exposure, and notify the control room that you are finished.
Dose Map:
### Table 15: Assessment Activity Data

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<th>training</th>
<th>Dose (mrem)</th>
<th>Comp. Time</th>
<th>Rad. A</th>
<th>Score 1</th>
<th>Loc Sel.</th>
<th>Score 2</th>
<th>Path</th>
<th>Score 3</th>
<th>Location</th>
<th>Score 4</th>
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</table>
Pre-Experiment Survey:

1. Subject Number:

2. Age:

3. Occupation:

4: How long have you been in your current position?

5. Do you or have you ever had unescorted access to a nuclear power plant or Penn State’s Breazeale reactor?

6. If yes, how long ago was your last retraining?

7. How do you feel you learn best?
   A) Reading books or procedures
   B) Watching demonstrations
   C) Hands-on
   D) Classroom instruction
   E) Computer-based or web-based training
   F) Other

8. If other, please specify:

9. Have you ever visited Penn State’s CAVE or similar visualization facility?

10. On a scale of 1-10, one being not comfortable at all and 10 being completely comfortable, how comfortable are you with technology?

11. On a scale of 1-10, one being not a computer user and 10 being a power user, how comfortable are you with using a computer?
Pre-Experiment Survey Raw Data:

Table 16: Pre-Experiment Survey Data

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<th>Occupation</th>
<th>Experience</th>
<th>Badged</th>
<th>Learn Best</th>
<th>Visited CAVE?</th>
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Pre-Test:

1. What does the acronym ALARA stand for?
   Answer: As Low as reasonably achievable

2. What are the three major considerations for controlling/reducing exposure to radiation?
   Answer: Time, Distance, Shielding

3. If a source is measured to be 10 mR/hr at 1 foot away, approximately what will the survey meter read at a distance of 2 feet?
   A) 5 mR/hr
   B) 2.5 mR/hr
   C) 10 mR/hr
   D) 3 mR/hr
   Answer: B

4. If you double your distance between you and a source, how much will your dose decrease?

5. If you stand in a room with a radiation field of 10 mR/hr for 12 minutes, about how much radiation have you received (in mrem)?
   Answer: 2 mrem

6. Which path in the image has the lowest radiation dose?
A) A
B) B
C) C
D) D
Answer: A
**Pre-Test Results – Raw Data:**

**Table 17: Pre-test Results**

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<td>?</td>
<td>location, location</td>
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<tr>
<td>2</td>
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<td>No Idea</td>
<td>Wearing the appropriate gear?, Be aware of your surroundings?, No Idea</td>
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<td>2 mR/hr</td>
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<td>Allowable Levels at Radiation Awareness</td>
<td>time, distance, shielding</td>
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</tr>
<tr>
<td>4</td>
<td>61</td>
<td>atomic level and radiation awareness</td>
<td>distance from source, radiation level, duration of exposure</td>
<td>B</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>5</td>
<td>58.33</td>
<td>Something Something and Radiation Awareness</td>
<td>B</td>
<td>B</td>
<td>2 mR</td>
<td>B</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>Not sure</td>
<td>Staying away from it, Some sort of protection, Not sure</td>
<td>C</td>
<td>D</td>
<td>50 mrem</td>
</tr>
<tr>
<td>7</td>
<td>83.33</td>
<td>As low as reasonably achievable</td>
<td>distance, shielding, time</td>
<td>D</td>
<td>B</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>61</td>
<td>A? L? A? Radiation Awareness</td>
<td>strength of source, distance from source, protective shielding</td>
<td>B</td>
<td>B</td>
<td>2 mR</td>
</tr>
<tr>
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<td>Alarming lethal amounts of radiation afloat</td>
<td>mutations, health, ecosystem</td>
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<tr>
<td>10</td>
<td>0</td>
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</tr>
<tr>
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<td>A</td>
<td>2 mrem</td>
</tr>
<tr>
<td>12</td>
<td>24.67</td>
<td>containment, distance, duration</td>
<td>C</td>
<td>D</td>
<td>2</td>
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<td>A</td>
<td>2</td>
</tr>
<tr>
<td>14</td>
<td>61</td>
<td>no idea</td>
<td>How much radiation, How long exposure time is, Distance from source</td>
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<td>B</td>
<td>2 mrem</td>
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<tr>
<td>15</td>
<td>50</td>
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<td>B</td>
<td>no idea</td>
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<tr>
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<td></td>
<td>B</td>
<td>B</td>
<td>B</td>
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<td>17</td>
<td>72.17</td>
<td>Awareness of Liquor Abuse in Rural Alabama</td>
<td>barriers, distance, proper equipment/attire</td>
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</tr>
<tr>
<td>18</td>
<td>16.67</td>
<td>ALA?? Radiation Awareness</td>
<td>Protective gear, Knowledge, Reducing exposure time</td>
<td>A</td>
<td>A</td>
<td>??</td>
</tr>
<tr>
<td>19</td>
<td>77.67</td>
<td>As Low As Reasonably Applicable</td>
<td>time, distance, protection</td>
<td>B</td>
<td>B</td>
<td>2</td>
</tr>
<tr>
<td>20</td>
<td>22.17</td>
<td>distance content</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>72.17</td>
<td>distance from source</td>
<td>B</td>
<td>B</td>
<td>2</td>
<td>B</td>
</tr>
<tr>
<td>22</td>
<td>33.33</td>
<td>A</td>
<td>A</td>
<td>2 mrem</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>50</td>
<td>B</td>
<td>C</td>
<td>2</td>
<td>B</td>
<td></td>
</tr>
</tbody>
</table>
Post-Test

1: What does the acronym ALARA stand for?  
Answer: As Low as Reasonably Achievable

2. What are the three considerations for controlling and reducing exposure to radiation? (the three components of ALARA)  
Answer: Time, Distance, and Shielding

3. If you are standing 3 feet from a source, and you want to cut your dose in half, about how far away do you need to be away from the source?  
A) 6 feet  
B) 5 feet  
C) 4.25 feet  
D) 9 feet  
Answer: C

4. If you are doing a job in a radiation field of 60 mR/hr, and it takes you 20 minutes to complete the job, assuming radiation is predominantly from gamma-emitters, about how much radiation have you received (in mrem)?  
A) 10 mrem  
B) 20 mrem  
C) 60 mrem  
D) 30 mrem  
Answer: B

5. You have to choose between two paths to enter an area. One path has a radiation field of 100 mR/hr and requires 5 minutes to traverse, while the second path has a radiation field of 40 mR/hr and requires 15 minutes to traverse. Which path would you take to minimize your radiation exposure?  
A) The first  
B) The second  
Answer: A

6. Which path in the image has the lowest radiation dose?
A) A
B) B
C) C
D) N/A
## Post Test Results – Raw Data:

Table 18: Post-test Results

<table>
<thead>
<tr>
<th>GRADE</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>66.67 as low as reasonably achievable</td>
<td>time, distance, shielding</td>
<td>D</td>
<td>B</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>2</td>
<td>66.67 as low as reasonably achievable</td>
<td>time, distance, shielding</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>3</td>
<td>100 as low as reasonably achievable</td>
<td>distance, time, shielding</td>
<td>C</td>
<td>B</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>4</td>
<td>100 as low as reasonably achievable</td>
<td>distance, time, shielding</td>
<td>C</td>
<td>B</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>5</td>
<td>83.33 As Low as Reasonably Achievable</td>
<td>time, distance, shielding</td>
<td>D</td>
<td>B</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>6</td>
<td>50 as low as relatively acceptable</td>
<td>time, distance, shield</td>
<td>D</td>
<td>B</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>7</td>
<td>83.33 as low as reasonably achievable</td>
<td>time, distance, shielding</td>
<td>B</td>
<td>B</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>8</td>
<td>66.67 As Low as Reasonably ?</td>
<td>distance, time, shielding</td>
<td>C</td>
<td>B</td>
<td>A</td>
<td>D</td>
</tr>
<tr>
<td>9</td>
<td>66.67 As low as reasonably achievable</td>
<td>shielding, timing, distance</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>10</td>
<td>77.67 As low as reasonably approachable</td>
<td>time, distance,</td>
<td>C</td>
<td>B</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>11</td>
<td>66.67 As low as reasonably achievable</td>
<td>Time Distance Shielding</td>
<td>C</td>
<td>B</td>
<td>B</td>
<td>D</td>
</tr>
<tr>
<td>12</td>
<td>83.33 as low as reasonable achievable</td>
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<td>B</td>
<td>A</td>
<td>B</td>
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<td>61 as low as reasonably acceptable</td>
<td>distance, shield, time</td>
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<td>B</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>14</td>
<td>83.33 as low as reasonably achievable</td>
<td>time, distance, shield</td>
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<td>B</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>15</td>
<td>100 As Low As Resonibly Achievable</td>
<td>Shielding, Time, Distance</td>
<td>C</td>
<td>B</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>16</td>
<td>77.67 as low as reasonably achievable</td>
<td>distance, barrier, time</td>
<td>C</td>
<td>B</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>17</td>
<td>44.33 At Least? Reasonable ?</td>
<td>Time, Distance, Apparel</td>
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<td>B</td>
<td>B</td>
<td>B</td>
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<td>B</td>
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<td>B</td>
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<tr>
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<td>B</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>21</td>
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<td>Time Distance Rate</td>
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<td>B</td>
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<td>22</td>
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<td>B</td>
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<tr>
<td>23</td>
<td>83.33 As Low As Resonably Achievable</td>
<td></td>
<td>C</td>
<td>B</td>
<td>A</td>
<td>B</td>
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</tbody>
</table>
Post-experiment Survey:

Computer Based Training (power point and PDF) only w/ CAVE assessment
CAVE training (CBT PLUS hands on in virtual environment) w/ CAVE assessment

On a scale of 1-10, 1 being extremely difficult and 10 being simple, was it difficult to learn to use the virtual environment?

On a scale of 1-10, 1 being more confused and 10 being fully understand, after the training how well do you think you understand the Time and Distance components of ALARA?
On a scale of 1-10, 1 being not helpful and 10 being extremely helpful, was the practical exercise helpful to your radiation awareness?
On a scale of 1-10, 1 being not helpful and 10 being extremely helpful, was the computer based training (PowerPoint and PDF) helpful to your radiation awareness?
On a scale of 1-10, 1 being poorly and 10 being excellent, how well do you feel you performed on the final activity in the CAVE?
### Table 19: Post-experiment Survey Results

<table>
<thead>
<tr>
<th>Subject#</th>
<th>Learn VE</th>
<th>Time dist</th>
<th>Practical Helpful?</th>
<th>CBT Helpful?</th>
<th>CAVE Perf.</th>
<th>Comments</th>
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<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>7</td>
<td>Book training was next to worthless. If I felt even marginally more comfortable with the virtual reality I could have used it much more effectively. Would attribute time lags to running into walls more so than not understanding what needed to be done and what the desired outcome was.</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>7</td>
<td>7</td>
<td>9</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>10</td>
<td>10</td>
<td>8</td>
<td>10</td>
<td>Awesome cave!</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>8</td>
<td>7</td>
<td>10</td>
<td>6</td>
<td>I don't think the CAVE necessarily improved my knowledge, however, I think the simulation would be helpful in preparing someone for task management within a plant (e.g., learning what preparation would have been helpful prior to entering the simulation).</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>9</td>
<td>9</td>
<td>8</td>
<td>6</td>
<td>I feel like I lingered more than an experienced worker with previous hands on experience may have during the final activity. More experience in a CAVE environment could have slightly increased my performance as well.</td>
</tr>
<tr>
<td>6</td>
<td>9</td>
<td>6</td>
<td>9</td>
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<td>6</td>
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<td>9</td>
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<td>8</td>
<td>w00t!</td>
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<tr>
<td>11</td>
<td>9</td>
<td>10</td>
<td>10</td>
<td>3</td>
<td>7</td>
<td>Seeing distances is more beneficial than just seeing numbers representing distances.</td>
</tr>
<tr>
<td>12</td>
<td>7</td>
<td>5</td>
<td>8</td>
<td>3</td>
<td>7</td>
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<tr>
<td>14</td>
<td>8</td>
<td>10</td>
<td>10</td>
<td>7</td>
<td>9</td>
<td>The Cave activity helps you to learn and practice some important elements of radiation awareness.</td>
</tr>
<tr>
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<td>10</td>
<td>10</td>
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<tr>
<td>16</td>
<td>10</td>
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<td>8</td>
<td>10</td>
<td>8</td>
<td>I should have used a calculator during the final quiz. The virtual reality was easy to use and navigate. The system seemed to be very nice and informative.</td>
</tr>
<tr>
<td>17</td>
<td>9</td>
<td>9</td>
<td>10</td>
<td>4</td>
<td>5</td>
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<td>18</td>
<td>8</td>
<td>10</td>
<td>10</td>
<td>8</td>
<td>10</td>
<td>The virtual tool is hard to read at times because the display is hidden behind the unit or the virtual hand.</td>
</tr>
<tr>
<td>19</td>
<td>9</td>
<td>9</td>
<td>10</td>
<td>7</td>
<td>8</td>
<td>I feel that the CAVE training really helped me understand the 3-d nature of radiation.</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>10</td>
<td>5</td>
<td>5</td>
<td>9</td>
<td>Being in the cave was fairly intuitive. It runs much like a video game would which I have had plenty of experience with.</td>
</tr>
<tr>
<td>21</td>
<td>9</td>
<td>10</td>
<td>10</td>
<td>9</td>
<td>9</td>
<td>I thought this was very fun and it was also a great way to learn about radiation training and the hazards of Radiation. One thing that would be even better is to incorporate a suit that emits pulses to the body to simulate high amounts of radiation exposure if possible.</td>
</tr>
</tbody>
</table>
Observations:

Observations were recorded as each subject completed the experiment trials. These notes are transcribed for each subject here.

Subject 1 – CBT only:

- Task 1: Navigated into the barrels in area 1
- Task 1: Found the source
- Task 2: “spot A is safer”
- Task 3: “B is safer”
- Task 3: returned from last area via lower dose path
- Poor navigation at first, but improved
- Got turned around on path selection task

Subject 2 – CBT only:

- Task 1: source was “a lot” (hit source dead on and exposure spiked)
- Task 2: found correct location, noted hazard of barrels
- Task 3: Took path A 2 times and then path B
- Task 4: located source in last tank of approximately 20 mR/hr
- Returned to entrance via path B
- No issues observed
- Received significant exposure on first task
Subject 3 – CBT only:

- Maze: no trouble navigating, thoroughly explored maze
- Task 1: located source – front of barrel
- Task 1: thorough search and survey
- Task 1: looked at instructions while standing in hot zone
- Task 4: located source of magnitude greater than 20 mR/hr in 3rd storage tank
- Task 4: noted additional source in barrel
- Kept in contact with control room throughout
- Very thorough
- Took one path on the way in to complete task 4 and the other on the way out
- Took longer than expected to complete tasks, but thoroughly surveyed all areas of most rooms

Subject 4 – CBT only:

- Task 1: Completed a quick search, found source of 220 mR/hr in center barrel of back row
- Task 2: Selected area A “quick”
- Task 3: used path B on the way to perform Task 4, tested path A briefly then returned via path B
- Task 4: correctly located hot spot on tank 3 of approximately 20 mR/hr
- Very good performance
• Demonstrated verbal knowledge of material in CBT – used terminology “low dose area”, head level

• Applied information well.

Subject 5 – CBT only:

• Task 1: located source in middle barrel in the back row of 1000 mR/hr
• Task 1: Squeezed back into the barrels
• Task 1: Spent a lot of time around the hot spot
• Task 1: Spent ~ 4 minutes on task 1, longer then all others.
• Task 3: Entered via Path A, then went back on Path B, traversed B again to get to Room 5
• Task 4: Found source inside of Tank 3 of 140 mR/hr (detector was inside of tank)
• Returned to entrance via Path B
• Careful and deliberate, studied CBT material much longer than others
• Clear demonstration of the competing effects of “doing a good job” and minimizing dose. Judged to have chosen the former
• Appeared to know the material, used the terminology, but failed to apply the information
• Used low-dose areas
• “I was in there way too long, wasn’t I?”
**Subject 6 – CBT only:**

- Task 1: Searched for less than 1 minute, found source of 11 mR/hr in the back row
- Task 3: Tested path B, backtracked, then took A and backtracked
- Task 4: Located source in 3rd Tank, 18 mR/hr
- Serialized tasks vs. big picture: serial
- Quick, low dose, but perhaps not thorough enough especially in 1st area that resulted in a low dose since the subject was never exposed to the “hot” barrel
- Not as efficient with path selection task, traversed multiple times.

**Subject 7 – CBT only:**

- Task 1: Located source of 10 mR/hr in corner
- Task 2: Identified the barrels as a hazard
- Task 2: surveyed up and down
- Task 2: Used low dose area 2 times
- Task 3: Took path A on the way to area 5 then looked at B, re-traversed B on the way to area 5
- Task 4: Identified source in 3rd tank of 50 mR/hr
- Video Game Mentality: characterized by poor survey of first area, quick completion time, and low dose
- “be sure to minimize radiation by taking this path”
- Low dose resulted from not finding the hot-spot in the first area
• Subject mentioned not even wanting to take path A in the third task
• Ok understanding of material, marginal application

Subject 8 – CBT only:

• Maze: Seemed comfortable with navigation
• Talked as he completed tasks
• Task 1: Measured source to be 16 mR/hr in the back corner
• Task 1: Survey appeared “poor”
• Task 2: Selected location A based on lower readings and good access
• Task 3: Took path A first and then took path B down and back
• Task 4: Located source in 3rd tank, performed a 3-D survey
• Talked aloud as he completed the tasks
• Took path B three times out-in-out.

Subject 9 – CBT only:

• Task 1: Located source of 140 mR/hr in middle barrel of back row
• Task 1: Quickly performed a thorough survey of the barrels
• Task 1: Paused in back row of barrels
• Task 2: Performed a 3-D survey, Selected location A based on 12 vs. 15 mR/hr
• Task 3: Up A, down B, up B
• Task 4: Measured 30-20-10 for the three tanks in the room
• Task 4: Performed a 3-D survey
• Thorough, quick, low dose
• Clearly learned something from the CBT, demonstrated knowledge, but spent a long time studying
• Subject had low quiz scores

Subject 10 – CBT only:

• Task 1: performed a 2-D survey
• Task 1: Located source of 130 mR/hr in the middle barrel of the back row
• Task 1: Looked at area in the barrels
• Task 2: performed a spatial study, low and high
• Task 3: Up A, Down B, Up B
• Task 4: Surveyed both sides of the room, up and down
• Task 4: found source in 3rd tank at head level

Subject 11 – CAVE training:

• Training Time: 14 minutes
• Task 1: “I was really far away”
• Task 2: only went part of the way into the room, didn’t measure location B since “radiation level was increasing fast”
• Task 3: Surveyed path B first after seeing “radiation area” sign at entrance to path A
• Task 3: Looked at number on A and decided against walking all the way down the path
• Subject did not appear comfortable with tasks
• Used low-dose area twice

Subject 12 – CAVE training:

• Training time: 15:38
• Task 1: measured source of 65 mR/hr in the middle barrel of the back row
• Task 1: searched hot barrel four times
• Task 1: used low-dose area to report results
• Task 2: measured barrels, identified barrels as hazard
• Task 3: surveyed path A first, back on B then up A
• Task 3: Identified hot spot on path A
• Task 4: Identified source in 3rd Holding tank
• Task 4: Thoroughly surveyed area, 3-D survey high to low
• Subject didn’t seem comfortable with navigation
• Did subject understand 360° nature of the CAVE?
• Had trouble reading the meter at times
• Did a thorough job locating the hot-spots
• “next worker will probably get a lower dose”
Subject 13 – CAVE training:

- Training time: 13:37
- Task 1: Quick survey, kept distance from barrels
- Task 1: Peak source was middle barrel of back row, 12 mR/hr
- Task 2: Max was at B, at head level
- Task 2: Worker should try to stay low
- Task 3: Tested A first, then back on B
- Task 3: Noted hot spot on Path A – “if you have to take path A, stay as far away from tank as possible”
- Task 3: Stay close to the wall on path B
- Task 4: Located source on third tank, “higher up”
- Task 4: Good 3-D survey
- Used low-dose areas
- Flipped through papers in the CAVE, study time was low
- Seemed to really “get it”, good application

Subject 14 – CAVE training:

- Training time: 17:10
- Task 1: Squeezed through barrels, located source in back row center barrel 30-40 mR/hr
- Task 2: Area A – 11.86, Area B – 14.5, noted barrels as hazard
- Task 3: Tested A first, then B
- Task 4: waited in low-dose area
- Task 4: Surveyed side to side
- Task 4: Located source at head level in last tank on the left 44 mR/hr
- Slow to learn navigation – non-gamer, Older than other subjects (47)
- Seemed to pick-up and apply material
- Found all sources and performed 3-D surveys

Subject 15 – CAVE Training:

- Training time: 13:46
- Task 1: located source, back row center 60 mR/hr
- Task 1: walked in between barrels, located 2\textsuperscript{nd} source in middle of barrels
- Task 2: located source at high level at location B
- Task 3: Up A, Down B, Up B
- Task 4: located source in 3\textsuperscript{rd} Tank at head level between 30 and 60 mR/hr
- Task 4: Performed 3-D survey
- Subject was a Gamer

Subject 16 – CAVE Training:

- Training Time: 12:42
- Task 1: Source located in back corner by barrels, 8-12 mR/hr
• Task 1: Surveyed outside of barrels
• Task 1: “Looks different than on paper”
• Task 2: Selected location A, noted hot spot in 4th barrel
• Task 3: Up A, Back B, Up A
• Task 3: Noted hot spot on path A
• Task 4: Located hot spot of 20 mR/hr on tank 3
• Quick survey of area 1, missed source, didn’t survey barrels closely enough

Subject 17 – CAVE Training:
• Training Time: 12:06
• Task 1: Went down one side only, quick survey
• Task 2: Selected location A due to lower radiation readings
• Task 3: up A, Down B, up B
• Task 4: used low dose area
• Task 4: found source in 3rd Tank, 30 mR/hr
• Quick survey, missed room 1 hot-spot
• Surveys looked very 2-D

Subject 18 – CAVE Training:
• Training Time: 13:06
• Task 1: Max source was 7 mR/hr in towards center of room
• Task 1: Stayed back against wall

• Task 2: Location A is better

• Task 2: high radiation to left (barrels)

• Task 3: entered via path A, performed task 4, left via path B

• Task 4: Located source on 3rd tank, 27 mR/hr

• Subject was familiar with computers

• Asked “what is maximum dose I can receive before I have to abort”

• Used low dose area 3x

• Demonstrated application of radiation awareness, terminology

• Surveys were too quick

**Subject 19 – CAVE Training:**

• Training Time: 12:59

• Task 1: found hot spot measuring 6.75 mR/hr in back corner

• Task 1: Noted radiation area sign at entrance to room

• Task 1: Stayed away from barrels

• Task 2: watched meter as he completed the task

• Task 2: Noted barrels as a hazard

• Task 3: slowly moved up path A, then backed out, before taking path B

• Task 4: located source at head level (50 mR/hr)
• Seemed to understand time, distance, and shielding and ALARA from the reading, used terminology
• Watched meter and adjusted path away from source.
• Thorough surveys in all spaces except the first
• Stayed away from radiation, seemed to hit source in area 5 which is where majority of exposure came from

**Subject 20 – CAVE training:**

• Training Time: 13:54
• Task 1: Located source, back middle barrel, 150 mR/hr
• Task 1: surveyed along top of barrels, found hotspot and got out
• Task 2: Measured 10 vs. 12 mR/hr, selected location A
• Task 3: Skipped path A initially and took path B
• Task 3: Briefly looked at Path A on the way out, determined it was “hotter” and exited via path B
• Task 4: located source in 3rd Tank, 20 mR/hr
• Stayed close to the wall on the way out
• Performed a quick survey in area 2
• Appeared to plan based on “last week’s” dose map
• Used low dose area
Subject 21 – CAVE Training:

- Training Time: 18:00
- Task 1: found source, last row, middle barrel > 100 mR/hr
- Task 1: located second source in the middle of the barrels
- Task 1: Thorough survey, low exposure
- Task 3: Selected path B, said to stay along wall
- Task 3: Recommended path B initially based on “old” dose map
- Task 3: Did try path A to make sure
- Task 4: located source in 3rd tank, 20 + mR/hr
- Performed tasks in reverse order (task 4 first)
- AE student: better spatial awareness?
- Finished task 1, then walked back through to double check path selection, this cost time and dose, but ensured that all tasks had been completed
- Best planning, by far, very unique

Subject 22 – CBT only:

- Task 1: found source, back row center barrel, 100 mR/hr
- Task 1: Surveyed around barrels twice
- Task 3: up A, down B, up B
- Task 4: Surveyed room in 2-D
- Task 4: Found source in 3rd Tank, 20 mR/hr
• Slow on a few tasks, thorough though

Subject 23 – CAVE Training:

• Training Time: 13:58
• Task 1: Located source, back row, center barrel 65 mR/hr
• Task 1: Went into barrels, climbed over barrels
• Task 2: Looked at both locations 2 times
• Task 2: “watch out for barrels and tank”
• Task 3: Up B, Down A, up B
• Task 4: Walked around area 2 or 3 times
• Task 4: located source in 3rd Tank, 20 mR/hr
• Very short study time, “I’m a fast reader”
VITA

Vaughn E. Whisker III

Vaughn E. Whisker III was born in 1975 in Bitburg, Germany. He showed an early interest in science and displayed a curiosity in how things work, which led him to pursue a career in engineering. High school projects on the accidents at Chernobyl and Three Mile Island and a report on particle accelerators focused his attention on nuclear engineering. He began his studies at Penn State in the fall of 1993, supported by an Air Force ROTC scholarship. He earned a Bachelor of Science in Nuclear Engineering with a minor in Military Studies in 1997, a Master of Science in 1999, and a PhD in 2008.

Mr. Whisker is currently an engineer with the Visualization Group (SEALab) at Penn State's Applied Research Lab. At the SEALab, he supports design reviews for shipbuilding programs using full-scale virtual reality mockups and develops virtual reality applications for DoD and Commercial sponsors. His research is focusing on using full-scale virtual reality mockups for training applications.

After earning his master’s, Mr. Whisker spent 4 years working for the Nuclear Safety Center at Penn State - performing safety analysis calculations for a fast burst reactor, working with the TRAC series of codes, and developing VR applications for design review of next generation nuclear power plants. He has served as an officer in the American Nuclear Society student chapter at Penn State and also served as an at-large board member of the Penn State Nuclear Engineering Society. He is a member of Tau Beta Pi, Alpha Nu Sigma, American Nuclear Society, NA-YGN, and the Penn State Alumni Association. Mr. Whisker resides in State College, PA.