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REVOLUTIONARY TECHNOLOGIES FOR THE NEXT GENERATION CONTROL ROOM

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ABSTRACT

As the current nuclear operator work force reaches retirement age, a new generation of operators is entering the workforce that is educated in and familiarized with advanced digital human system interface devices and less so with the analog equipment of legacy plants. To accommodate these changing workforce demographics, new products will need to incorporate advanced digital technologies which the new generation is familiar with and knowledgeable about.

To determine which new products to develop, current and near-term technologic trends that have potential to be applied to control rooms were explored. Literature research in the fields of science and technology, nuclear control rooms, non-nuclear (oil, gas, distribution) control rooms, and military technologies along with customer interviews were conducted to develop a list of potential technologies.

The technologies selected for further research were chosen based on greatest potential application in control rooms and short-term feasibility for implementation.

These technologies were researched to determine how the technology functions, potential applications for nuclear power plant control rooms, and feasibility for becoming an actual near-term product. The results of this research are used to provide recommendations for technologies that could be implemented in the next wave of nuclear power plants and for upgrades in existing plants.

This paper describes the methodology for selecting the technologies to research, details about the technologies and their potential applications, and a summary of further work to be conducted.

Key Words: Cognitive Modeling, Interactive Displays, Haptic Technologies, Augmented Reality, Digital Pens and Paper

1 INTRODUCTION

With the resurgence of interest in nuclear power, much demand and focus has been placed on new reactor designs that are being developed, as well as digital upgrades for current nuclear power plants. For the first time in over 30 years, orders for new plants in the United States were placed. To remain competitive, Westinghouse is identifying and developing new products that increase safety and efficiency, while meeting customer requests for new technology.

The nuclear industry as a whole is also expected to see approximately 39% of the current work force reach retirement age by 2016 [12]. The new generation of operators that will be replacing the current work force is educated in and familiarized with advanced digital human system interface devices, such as computers and touch screens, and less so with the analog equipment of legacy plants [19]. To accommodate these changing workforce demographics, new products will need to incorporate advanced digital technologies which the new generation is familiar with and knowledgeable about.

This paper provides details for the top five technologies recommended for application in the next wave of nuclear power plants and for upgrades in existing plants, which consists of:

- Cognitive Modeling
- Interactive Displays
- Digital Pens and Paper
- Haptic Technologies
- Augmented Reality

This paper describes the methodology for selecting the technologies to research, details about the functionality of the technologies, potential applications of each technology, the feasibility for the technologies to become an actual near-term product, and a summary of further work to be conducted.

2 METHODOLOGY

To determine which new products to develop, a team was formed within Westinghouse Electric Company that was composed of members from three different Operator Interface Engineering (OIE) groups. Members were from the Human Factors and Operations (HF&O) group, the Human System Interface Design (HSI) group, and the Control Room Design (CRD) group. Each member was selected based on his or her background and skills. The member from HF&O provided expertise in the human factors field. The member from HSI provided expertise from the software field. The member from CRD provided hardware expertise.

Current and near-term technology trends that have potential to be applied to control rooms were explored. The scope of this project was limited to technologies that could be implemented within the next 5-15 years with relative ease and met a majority of the following criteria:

- Applicable to the operator interface (software and/or hardware)
- Applicable to the design process of the operator interface
- Applicable to the physical control room environment
- Technologies should be fully developed or in the final development stage
- Potential to increase safety and efficiency

Literature research in the fields of science and technology, nuclear control rooms, non-nuclear (oil, gas, distribution) control rooms, and military technologies along with customer interviews were conducted to develop a list of potential technologies.

The technologies selected for further research were chosen based on greatest potential application in control rooms and short-term feasibility for implementation. The resulting list of technologies consists of:

- Cognitive Modeling
- 3D Displays
- Interactive Displays
- Tablet/Slate Personal Computers (PCs)
- Augmented Reality
- Virtual Reality
- Haptics
- Speech Synthesis

- Speech Recognition
- Digital Pens and Paper
- Transparent Keyboard and Mouse Use
- Infrared (IR) Tracked Wireless Control
- Eye Tracking

These technologies were researched to determine how the technology functions, pros and cons of the technology, current nuclear power plant applications, potential applications for nuclear power plants, and feasibility for becoming an actual near-term product.

All of these technologies are worth considering for development in the next wave of nuclear power plants and upgrades to current power plants, but only Cognitive Modeling, Interactive Displays, Haptic Technologies, Augmented Reality, and Digital Pens and Paper are presented in this paper due to their feasibility for near-term implementation and the potential applications.

3 TECHNOLOGIES

This section provides details about the functionality for each technology, potential applications, and feasibility for becoming an actual near-term product. The technologies include Cognitive Modeling, Interactive Displays, Haptic Technologies, Augmented Reality, and Digital Pens and Paper.

3.1 Cognitive Modeling

Cognitive modeling consists of a cognitive architecture and a cognitive model. A cognitive architecture is used to develop cognitive models, and cognitive models are then used to provide input for designs.

3.1.1 Cognitive architecture

A cognitive architecture is a framework for how human cognition works. It looks like a programming language; however, its constructs reflect assumptions about human cognition. These assumptions are based on numerous facts derived from psychology experiments. A cognitive architecture integrates theories of cognition, visual attention, and motor movement and simulates the time course and information processing of cognitive mechanisms, such as changes of attention and memory retrievals, as well as external actions, such as movement of the fingers. The architecture also takes into account cognitive constraints, such as the limiting size of short term memory, the limiting field of vision, etc. Examples of information contained in a cognitive framework are how long it takes to look from one item/display to another, to move one hand a certain distance, to press down on a key, to retrieve long-term memory, etc. [1]

The human brain is one of the most complex systems known and there are a wide variety of interpretations of the complexity. This results in there being many different cognitive architectures, each with their own interpretation of how cognition works. These include: ACT-R, Apex, CLARION, EPIC, PRS, Soar, and many more [1].

3.1.2 Cognitive model

Cognitive models are an approximation of cognitive processes for the purpose of comprehension and prediction. They tend to be focused on a single cognitive phenomenon or process, how two or more processes interact (e.g., visual search and decision making), or to make behavioral predictions for a specific task. Cognitive models are composed using a cognitive architecture, incorporating the architecture’s view of cognition and adding assumptions about a particular task. A cognitive model contains information about a task or tasks and the relevant parts of the world in which the tasks take place [2].

3.1.3 Potential applications

A cognitive model could be used to find event and action timing, error areas, high workload areas, prediction of situation awareness, and the effects of different design options. This can be used to improve current interface design and provide input for interfaces in the design process. Examples include determining the best placement for controls and displays, what displays are needed, what information needs to appear on specific displays, and so forth.

The amount of time it will take to diagnose and resolve the cause of an alarm could be determined with a cognitive model, which can be used to help with the prioritization of alarms. An alarm that might be considered medium priority could actually be of high importance because of the amount of time it will take the operator to navigate the computer and physical interface to diagnose the problem and execute the required actions to resolve the cause of the alarm, and the chance of errors that may occur during this process.

A cognitive model could be used to determine how to structure a procedure to be the most efficient, least error-prone, and least amount of workload. For example, adding additional steps at one point might help reduce errors and/or workload.

A cognitive model could be used to identify error-prone and high workload points in a task. With these areas identified, solutions can be created to reduce error and decrease operator workload. Solutions can be compared as to their efficacy by using the cognitive model. The plant computer can then be programmed to display additional information at the appropriate locations to assist operators through these situations. For example, a display could open automatically that provides all the additional information an operator needs without having the operator search through all the displays, or important information that an operator needs to monitor can automatically become highlighted.

A cognitive model could help determine functional allocations for personnel and the level of automation necessary to handle crew high workload situations that takes advantage of human strengths and avoids human limitations.

A cognitive model could be used to assist with training. Since a cognitive model knows the correct procedures and actions for tasks, it can pinpoint at what points a trainee is making mistakes. This helps recognize a trainee's weakness, which can then be addressed through tailored training.

3.1.4 Near-term feasibility

The Nuclear Regulatory Commission (NRC) and the nuclear industry have developed and used cognitive models. One of the primary applications has been to investigate plant staffing issues [3]. Other applications have included the prediction of operator response to disturbance scenarios, the prediction of situation awareness, and as an extension to a task analysis to evaluate event timing and action, error rate, and the effects of performance shaping factors and workload [4][5][6]. The use of cognitive models in the nuclear industry has not been widespread and not all the possible applications of cognitive models have been implemented.

Cognitive modeling is a very valuable tool that has many potential applications that can greatly improve a plant's design with minimal costs. The models are accurate enough to provide beneficial information and guidance. This technology already exists, is proven to work, and has already been used successfully in the nuclear power plant industry. As a result, cognitive modeling is a product that can be quickly implemented in the design of new nuclear power plants and in upgrades of current nuclear power plants.

3.2 Interactive Displays

Interactive displays consist of a large group of different technologies that all perform a similar function. They provide the ability to directly interface with the user display in a physical manner and in multiple formats (e.g., finger, pen, objects). Simpler technologies can only handle one input at a time, whereas more advanced technologies can handle multiple inputs and multiple users (e.g., multiple fingers, pens, and/or objects).This allows for intuitive and fast manipulation techniques compared to traditional input devices, such as a computer mouse or keyboard.

3.2.1 Technologies

There are numerous technologies available for capturing this interactive input into the computer system from the display. These display technologies include, but are not limited to: resistive, surface acoustic wave (SAW), optical imaging, and capacitive.

3.2.1.1 Resistive displays

Resistive displays consist of two flexible and transparent layers that are coated with a resistive material and are separated by air and very small insulating particles. An electrical current is run through the layers coated in resistive material. When a force is applied to the top layer it connects to the bottom layer and an electrical circuit is completed which is sensed and located by a controller [7].

3.2.1.2 Surface acoustic wave displays

SAW displays use transmitting transducers, receiving transducer, and reflectors. An electrical signal is sent to the transmitting transducer, where it is then converted to ultrasonic waves. These waves are sent to the reflectors, which are placed along the edges of the screen. The ultrasonic waves are reflected to the receiving transducer, where they are converted back to electrical signals. If a person touches the screen with his or her finger, the waves become disrupted and absorbed. This disruption is detected by the receiving transducer and the location can then be determined [7].

3.2.1.3 Optical imaging displays

Optical imaging displays use optical cameras around the edges of the screen, behind the screen, or focused on the screen. The display field is then flooded with infrared light. When an object touches the screen, the cameras detect the disruption in the light and calculate the location of the touch. Optical imaging displays respond to touches from any object, such as fingers, gloved hands, or stylus pens, and at any location on the screen, even the corners [7].

3.2.1.4 Capacitive displays

Capacitive displays utilize a grid of transparent capacitors overlaid on the useable screen area. The human body has a natural capacitance associated with it which can draw a small current from each portion of the grid. Any touch on the capacitor grid will disrupt the inherent capacitance present on the display, which is detected by the sensing circuit and interpreted as a touch and/or movement [7][8].

3.2.2 Potential applications

A large interactive display could be used to provide a large mimic or graphical display of the plant that could be easily updated and changed. The touch capability could allow the operators to start with a high level overview of the entire plant, navigate down to specific systems and components, and control components using their fingers or objects. Multiple operators could interact with the same large panel display either for collaborative work or for separate purposes.

Touch screens currently are used for individual workstations to interface with equipment components. Some of the touch screen technologies, not currently being used, allow physical objects to be used to perform actions with the displays, allowing more natural and useful objects to be used for display interaction compared to simply touching graphics on a screen. For example, a physical mimic of a rotary switch could be placed on the display to toggle the start and stopping of a pump compared to touching or clicking a button on the screen. In addition, multi-touch functionality could be used to enhance collaboration between operators at individual workstations.

Touch screens provide the ability for operators to draw directly on the screen using fingers or a stylus. This would allow operators to make notes and point out specific items/values to other users for future reference. Control board operators used grease pencils to mark items on the control panels and instruments for reference. This vanishes with the incorporation of computerized control but touch screens can preserve this useful functionality.

Interactive displays would allow the operators to have virtual “stacks” of procedures that they can flip through easily. This mirrors what operators have been doing for decades with current paper procedures.

Portable interactive displays, such as tablet or slate PCs, can be used to obtain information about the plant, control the plant, take notes, and fill out reports and paperwork anywhere in the control room or in the field, rather than the operator being tied to a workstation. Any information on one portable display could be shared with all other displays, which could enhance communication between operators. In addition, portable interactive displays, components, and instruments could use a tagging system, such as radio-frequency identification (RFID) tags, such that when the portable display is near a component/instrument, relevant information is automatically displayed.

3.2.3 Near-term feasibility

Interactive displays are currently being successfully used in existing nuclear power plants. Examples include interaction with trend displays, executing soft control actions, and performing display-to-display navigation functions on graphic displays. Often these displays are small with limited functionality compared to the capabilities of today’s technology.

Interactive displays have been around for decades. As a result, the technology is relatively mature and has greatly advanced. With recent cost decreases in manufacturing and design, along with more accurate manufacturing processes, the implementation of touch screens has ramped up over the past five years and can be made available and implemented quickly. The potential impacts for having interactive displays in a control room are substantial and would be an invaluable resource for operators. As a result, interactive displays are a product that can be quickly implemented in the design of new nuclear power plants and in upgrades of current nuclear power plants.

3.3 Digital Pens and Paper

Digital pens and paper enable transmission of handwritten text into a digital format, which can be used in many programs like Word®[1], PowerPoint®, and Adobe® portable document format (PDF). This technology provides a way to interact with the digital world without losing the affordances of paper.

There are currently two types of products for digital pens and paper. One uses a pen with an embedded camera and a special pattern printed on paper, and the other uses a pen that transmits information acoustically to a receiver.

3.3.1 Camera and printed pattern

The first type consists of a digital pen and a special pattern printed onto paper. The pen looks, feels, and writes like a normal ballpoint pen but it also contains an integrated digital camera, an image microprocessor, and a mobile communications device for wireless connection. The paper contains a dot pattern that makes it possible for the digital pen’s built-in camera to detect pen strokes and record handwriting that can then be stored or sent digitally to a phone or computer. The pattern on each paper has a unique identity, so each page can be kept separate from another. This pattern can be printed on any type of ordinary paper. The pen comes with a cap that will prevent ink from being written on paper but will

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[1] Word, PowerPoint, and Adobe are trademarks or registered trademarks of their respective owners. Other names may be trademarks of their respective owners.

still produce digital writing. Some of the pens contain a microphone and speaker so that users can record what they hear and say to specific pages and play the recording back later directly from the pen or from the computer [9].

The data can be transferred wirelessly using Bluetooth®[2] via a mobile phone or by connecting to a computer via a universal serial bus (USB) port. The pen data includes what was written, the exact time when each stroke was written, who wrote them, the captured audio, and the identity of the paper form and of the specific pages [9, 10].

This technology has a programming language that allows the devices to be easily customized and provides a wide range of opportunities. Examples include being able to draw symbols on the paper that will attach pictures taken from a camera, or performing actions on a computer using gestures with the pen [9].

3.3.2 Acoustic pen and receiver

The other type of digital pen is based on the transmission of ultrasonic acoustic waves between two or more devices via a "Transmitter" and a "Receiver." The transmitter, embedded in the pen, sends a unique ultrasonic signal with specific time and spectrum characteristics assigned to each transmitter device to a receiver. The receiver uses the signals to measure the distance and position of the pen's tip. This technology supports the use of many devices simultaneously. The receiver can be attached to any paper and connects to the PC via any standard USB cable, Radio Frequency (RF), or Bluetooth Connectivity. Written or drawn information is displayed in real time on the screen or it can be stored in the pen and downloaded at a later time [11].

Using this technology, users can capture and display handwritten notes and drawings on a computer, transform handwritten notes to text with handwriting recognition software, have full mouse functionality with a computer, and share hand-drawn/written files via email and messaging applications – all without the need for special paper or a tablet computer. For mouse functionality, users can point and click on icons, drag and drop files, and scroll up and down inside documents [11].

3.3.3 Potential applications

Paper work that must be scanned and archived could be tracked and recorded using the pen. The information in the pen can be automatically uploaded into an electronic document management system as a PDF (no text conversion) or converted to a text document (Word, RTF, etc.) that is searchable and uploaded into the document management system. This could be used to archive copies of shift turnover meetings, emergency response meetings, notes taken in the field, equipment tagout information, etc.

Feedback could be provided to operators and supervisors completing standard paperwork that must be done in a particular way, such as procedures. For example, if the writer skips a checkbox or section of the form that must be filled or completed, the pen or connected phone or computer can audibly and visually alert the user to the missed section and provide details on the error.

Note taking could be enhanced by including recording time and user identity. In addition, audio and pictures can be captured and linked to specific notes. This could provide additional information not possible through writing. This information could make it easier to understand the notes that have been taken without confusion caused by difficulty in reading handwriting.

The user's writing with the digital pen could be projected on a large screen so that everybody in the room can see what is being written. The information could also be displayed remotely on computer screens so that remote collaboration can be performed. In addition, multiple people could interact with the

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[2] Bluetooth is a trademark or registered trademark of its respective owner. Other names may be trademarks of their respective owners.

same document and at the same time digitally using their own paper. This could be used, for example, to provide real-time feedback of notes field technicians are making, and can allow operators in the control room to interact with the field technicians through the shared digital document. For example, if field operators have a paper printout of a component they are looking at, they could point out any problems they see by drawing on it. This information can be viewed by operators in the control room or it could be saved and reviewed at a later time.

Paper could be reused by only making the writing digital. Users could choose to have all their drawings and writing appear only on the computer and not on actual paper. This makes it possible to reuse paper rather than having to constantly print more. This could be used for making notes on a piping and instrumentation diagram (P&ID) or procedure. The notes could be displayed on a computer screen and saved, but the paper could still remain clean and usable.

3.3.4 Near-term feasibility

Digital paper and pen technology provides many benefits at a very low cost. The technology is very customizable which allows the technology to be easily adapted to specific needs. Commercial products are available with a suite of applications and have been proven to be successful across several different industries, such as aviation, military, and healthcare. Digital paper and pen technology is a product that can be quickly implemented in the design of new nuclear power plants and in upgrades of current nuclear power plants.

3.4 Haptic Technologies

Haptic technologies take advantage of a user's sense of touch by applying forces, motions, and/or vibrations to the user. The simulated sensation associated with any form of haptic feedback can assist a user in the control of virtual objects and enhance a user's ability to remotely control devices and machines.

Several different forms of feedback exist to stimulate the user's sense of touch. The main types of haptic feedback are localized piezoelectrics, electrovibration, vibration, and surface alternation [15][16][17].

The two most promising types of haptic feedback are localized piezoelectrics and electrovibration. These two types of haptic feedback have the ability, for example, to simulate not only simple tactile feedback to acknowledge a button push, but to also give the user a sense of texture or depth. This allows the user to feel a button push or click and to feel the rotation of a scroll wheel.

3.4.1 Localized Piezoelectrics

Localized piezoelectric feedback works by placing multiple piezoelectric actuators under the touch surface. When the user touches the surface, voltage is supplied to all, a group of, or individual piezoelectric actuators depending on point of contact and how the system is programmed. When an actuator receives voltage, it deforms by bending or bowing in or out. This can be used to move the actuators themselves in and out of the touch screen, to move another object, such as a fluid-filled pouch, in and out of the touch screen, or to push the touch screen, causing it to move and bend. With the addition of sophisticated software, the technology can simulate a multitude of tactile feedbacks. For example, as users select or activate a digital button on a touch screen, they can feel movement in and movement out similar to a physical button [17][18].

3.4.2 Electrovibration

Electrovibration feedback works by creating an electrostatic force, which physically attracts the user's finger to the touch surface. The touch panel is made up of a thin layer of glass, an electrode, and an insulation layer. A periodic electric charge is applied to the electrode which in turn displaces charges within the insulation layer. The displacement of charges in the insulation layer creates an oscillating electric field. When the user's finger touches the panel a periodic motion of electric charges is induced in the user's finger creating an attraction force. This attraction force modifies the friction between the user's finger and the touch panel producing the sensation of tactile texture [15].

3.4.3 Potential applications

Touch screen displays with haptic feedback could be added to operator workstations to allow the operator to feel real-time feedback on actions taken to control the plant. Currently, feedback of soft control actuation is provided by auditory and visual feedback, which does not provide the operator a sense of satisfaction that a physical action has occurred. Providing soft controls with haptic feedback would allow a reconnection to the physical world for the operator. This reconnection provides a sense of when an action has really taken place. With customizable feedback solutions, the operator would be able to feel button presses, scroll actions, level movements, etc. This could be used to supplement or replace traditional plant hard controls.

Haptic feedback could be used in a virtual reality environment to provide the user with a physical mimic of the real-world interface. Current virtual reality control interfaces (e.g., glove systems) do not provide a real-world limit. For example, someone working in a virtual world may see a wall directly in front of them, but when they reach out to touch or interact with the wall there is no feedback to tell them they are hitting a physical limitation of the virtual world. Haptic feedback could also be used to provide simulated hard control interfaces with real world feedback.

Haptic feedback could be used to assist in the control of remotely-located robots. The remote control for the robot could provide haptic feedback when the robot approaches a wall or other type of obstacle. This could help warn users of the remote control and prevent them from accidentally having the robot hit an obstacle. In addition, the haptic feedback could change based on the speed of the robot's movement, providing an additional method of feedback of speed that does not require looking at a visual display.

3.4.4 Near-term feasibility

Several commercial solutions that utilize localized piezoelectrics and electrovibration are currently available. These commercial solutions could be licensed or used outright for incorporation into control screens in nuclear power plants. New software to provide the simulated interface will need to be developed for integration with the soft control software suite. Equipment qualification work will be required to provide assurance that these low level electric signals will not cause interference with safety equipment. With minimal upfront work, haptic feedback is a technology that can be quickly implemented in the design of new nuclear power plants and in upgrades of current nuclear power plants.

3.5 Augmented Reality

Augmented reality (AR) is a direct or indirect view of a real-world scene whose elements are enhanced by computer-based graphics. AR functions by enhancing the user's perception of a real world scene by presenting the user with additional information and details via a graphic display overlay.

Multiple methods exist to identify objects the user is viewing. Computer vision technology can identify features of real-world objects and surroundings. Computer vision can also recognize markers placed in the real-world environment beforehand to act as landmarks. Alternative methods of identifying objects include the use of electronic compasses, Global Positioning System (GPS), RFID tags, or inertial measurement units to estimate the location and orientation of the user's viewpoint. [13]

Tracking a person's location and movements is also an important part of augmented reality. This is accomplished through digital cameras, optical sensors, or other means. This information can be used to provide additional details and guidance to users and adjust the displayed overlay to correspond with the users' movements, actions, and direction of focus. [13]

There are three main display techniques for AR: handheld displays, head mounted displays (HMD), and spatial augmented reality (SAR). Handheld displays will not be discussed as they require the user to interface with an additional device and are not appropriate for control room use.

3.5.1 Head Mounted Displays

HMDs are primarily used by the military, where the AR display is built into the helmet used by pilots and other machine operators. This type of AR employs either optical see-through or video see-through technology. Optical see-through uses special mirrors that are partially transparent and pass real world information through, and reflect the overlay information into the user's eyes. Video see-through processes both the real world and overlay information into one feed for the user to view. Two cameras mounted on a person's head record the real world information. These images are then combined with the virtual overlay images and all of this is displayed to the user. [14]

3.5.2 Spatial Augmented Reality

Instead of an individual wearing or carrying the display device, SAR uses projectors to overlay information onto physical objects. Cameras are used to monitor the surface on which the display is projected. The virtual objects do not change as the observer moves and all users are presented the same information. This type of AR allows for higher resolution imagery and for a more collaborative environment. [13]

3.5.3 Potential applications

AR could be used to overlay additional information on operator displays to assist with daily tasks. Using an HMD would allow the operator to glance at a display to see additional information. The AR device could also allow the operator to select what type of augmented information to view. For example, the operator could choose to view computerized procedures displays, trend graphs, alarm panels, video feed from other portions of the plant, P&IDs, etc., that are related to the current display of focus.

On an operator display, AR could be used to overlay information that is dependent on a specific procedure step and related to that display. Using AR tracking, the device used to display the overlay information would recognize what display was being viewed, and could guide the operator to the correct screen for completing the procedure step by highlighting the correct navigation links. The AR could highlight the component or indication that is being referenced in the current procedure step. For example, if the operator is required to actuate a specific control, as he or she looks around the control board (physical or soft), the display could provide guidance on where to look for that specific control (up/down/left/right). Once the desired control is within the operator's field of vision, the augmented display would highlight or encircle the desired control device.

In addition, the procedure steps could be displayed on the AR device so that operators could be aware of what step they are on and future steps without having to go back and forth between either the paper procedures or the computerized procedures and the displays.

3.5.4 Near-term feasibility

Several commercial solutions currently exist that could be used to implement AR within the control room. The SAR technique could be used to develop a custom solution for use on physical control room boards without requiring advance tracking systems. If the operator becomes dependent on the system during plant transients, it is likely that the entire system would need to be classified as safety related. After any safety concerns are resolved, AR will be a technology that can be quickly implemented in the design of new nuclear power plants and in upgrades of current nuclear power plants.

4 CONCLUSIONS

As interest in nuclear power increases, technology changes and advances, and a new generation of operators enters the nuclear power plant industry, it is important that new products are identified and developed that will meet customers' demands for the next wave of nuclear power plants and upgrades for current nuclear power plants.

Technologies were explored that can be implemented within the next 5-15 years with relative ease; are applicable to operator interface, design process of the operator interface, or the physical control room environment; are fully developed or in the final development stage; and/or have potential to increase safety and efficiency in designs. This paper explored the top five technologies recommended for application in the next wave of nuclear power plants and for upgrades in existing plants. These technologies can be implemented now or in the near future and provide applications that can greatly improve and enhance the user experience, safety, and efficiency of the work associated with the control of nuclear power plants.

It is recommended to further research all thirteen technologies mentioned in the Methodology section, particularly the five technologies discussed in this paper, to determine exactly which products to use and how to incorporate these technologies into nuclear power plants. It is also recommended to implement these technologies now so that they can be incorporated into the design of the next wave of new nuclear power plant designs and upgrades for current nuclear power plants.

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