# Application of modern training technologies to improve safety in nuclear power plants

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***Abstract:*** *Simulation-based training has seen an increased use of extended reality, that is, augmented reality (AR), virtual reality (VR) and mixed reality (MR) displays. The health professions have been using VR for simulation-based training more extensively than others. This method can offer the possibility of immediate feedback, which promotes more accurate training to self-correct mistakes in environments that are otherwise risky or provide unsafe conditions. The nuclear industry has attempted to seize the same digital and educational transformation to train their personnel to handle dangerous scenarios.*

***KEYWORDS:*** *NUCLEAR FACILITIES, MODERN TRAINING TECHNOLOGIES, MANAGEMENT SYSTEMS, PROTECTION OF NUCLEAR INSTALLATIONS, REGULATORY FRAMEWORK*

## *1. Introduction*

Nuclear power is one of the most complex and responsible industries in the world, where the human factor plays a crucial role in ensuring safety.

Errors resulting from insufficient training or incorrect personnel response can have serious consequences for the facility, the environment and society.

Therefore, training and qualification of personnel are key elements of the safety management system.

As technology advances, traditional forms of training - lectures, seminars, and classroom exercises - are increasingly being supplemented by innovative methods such as virtual reality (VR), augmented reality (AR), and computer simulators.

These approaches provide new opportunities for building practical skills in a safe and controlled environment, without risk to the actual installation.

## *2. Modern technologies in the training of nuclear power plant personnel*

Appropriate training ensures that each member of staff is informed about the meaning and significance of the work they are performing and about how their work contributes to safety and to the achievement of the Company's goals.

The application of virtual reality (VR) and augmented reality (AR) allows trainees to immerse themselves in a fully realistic three-dimensional environment where they can interact with equipment, systems, and emergency scenarios using one-on-one simulations.

This way, operators and technical specialists acquire skills not only through theoretical exercises but also through practice-based learning.

Research by Masiello et al. (2022) [1] shows that VR training significantly improves the perception of emergency situations procedures and response.

Participants in a pilot study reported feeling more confident when performing real-life tasks after training in a simulated environment.

Similarly, Satu and colleagues (2024) [2] analyze the implementation of VR and AR platforms for training field operators of nuclear power plants.

The authors found that simulated scenarios led to better team coordination and faster identification of potential risks.

In addition, real-time visualization of complex processes facilitated a deeper understanding of technological dependencies in nuclear systems.

## *3. Safety and work culture benefits*

One of the main advantages of modern training technologies is the ability to reduce the risk of human error - a leading factor in most accidents in the nuclear industry.

VR and simulators allow emergency situations to be replayed multiple times, which develops automated responses and critical thinking in staff.

Furthermore, through integrated monitoring and performance analysis systems, trainees receive objective feedback - data on accuracy, response time, consistency of actions, and decision-making.

This information allows for a more accurate assessment of competence and identification of areas where additional training is needed.

As Roy et al. (2024) [3] point out, the use of digital twins in combination with VR/AR technologies creates an opportunity for continuous monitoring and improvement of operator behavior.

This achieves higher reliability of safety systems and builds a stable safety culture in which training is not a one-time process but a continuous cycle of improvement

## *4. Integration of modern technologies into training and competency assessment programs*

The International Atomic Energy Agency (IAEA) emphasizes in its documents, such as "Training and Qualification of Nuclear Power Plant Personnel: A Guidebook" (IAEA TRS No. 380) and "Use of Nuclear Power Plant Simulators for Education and Training" (IAEA TECDOC-1983), that the implementation of simulators and digital platforms is a key element for the sustainable development of nuclear safety [4,5].

These guides recommend the application of a systematic approach to training (SAT), which includes needs analysis, design, development, implementation, and evaluation of effectiveness.

### *4.1. Implementation of simulator training*

Briefing of the control room team is typically conducted prior to any simulator demonstration, training exercise or assessment scenario being carried out. Such a briefing may be conducted in the classroom or on the simulator floor.

In most cases, a prepared brief for a combination of training scenarios, or the simulator exercise guide (for one off exercises) is used as the lesson plan by the instructor.

These briefings usually cover team member assignments (roles), plant initial or as found conditions and immediately prior to the commencement of the exercise, a shift handover and control board (panel) walk down by the trainees.

For demonstration or training scenarios the training will also include all relevant information about the specific scenario and any

refresher training regarding fundamentals theory, plant systems or components re-familiarisation training, needed to support the exercise:

- Prepared material, such as work orders or tag-outs, etc., should be provided prior to starting the exercise to maximize realism during training scenarios;

- Any simulator related issues to be included as part of the briefing, if relevant to the exercise being run, e.g. any simulator fidelity issues that may have an adverse effect on the training exercise.

It is normal practice to agree a multiple-year training curriculum with the line; typically, 3-5 years. A training plan is developed, captured, recorded and agreed by operations management, via the relevant training oversight committee.

This ensures all mandatory training requirements, arising training needs, important topics, e.g. operational learning are reviewed for their training need and repeated systematically as required to maintain the knowledge, understanding and practice of all Operator Fundamentals to the expected standard.

The curriculum (task to training matrix) typically ensures that the identified training aims, and objectives are captured in the training scenarios, and are trained during initial training, as well as ensuring that they are repeated continuously in a systematic manner, as per the identified need stated by the responsible training committee.

The purpose of the curriculum is to ensure that the essential topics are identified and training of these topics repeated systematically over a specified time span to ensure that the knowledge and practical skills of the operators remain at the expected standard (as defined in NPP standards and expectations documentation).

This overview of the training needs identified, when the training was completed and the level of proficiency attained by the individual trainees, will help prevent the gradual degradation of operator standards over time, after completion of initial training and authorization.

The analysis stage of the SAT process is essential to identifying:

- Who is going to be trained using the simulator? (e.g. operators, systems engineers, fault studies & research engineers, maintenance department, operator technicians, etc.);

-What they are required to be trained in? (operators requiring full fidelity of control room operations, fault studies engineers looking at cause and effect scenarios, operator technicians training on an individual plant item or system);

- What level of training must be attained by the trainee? (formal assessment for staff and at the other extreme running a demonstration exercise for management, dignitaries or the regulator).

Resourcing the analysis stage of the SAT process adequately, prior to contacting a simulator manufacturer, will help ensure that a clear picture of the simulator training requirements is communicated to the vendor accurately when specifying and finally placing a contract to purchase or update a site simulator.

Getting a clear understanding of the simulator training requirements can prevent the buyer from over specifying or under specifying their new simulator performance requirements. It will provide for an accurate plan of training needs to ensure that future simulator availability can be met, with provisions being considered towards future simulator requirements/modifications and possibly prevent a large, avoidable budget overspend including crossing time schedules.

With the capabilities of the modern simulators described, it is now realistic to incorporate digitally supported training practices from the outset, of any operations training programme in the technical and knowledge-based training of such topics, as:

- Nuclear physics principles;

- Water-steam cycles;

- Thermal core design;

- Design basics;

- Safety margins;

- Safety barriers;

- Safety systems (including plant configuration, e.g. isolation valves);

- Operational systems (particularly those having an impact on safety related plant availability, possible precursors to an event if mis-managed);

- Control systems and reactor protection systems;

- Design basis accidents;

- Beyond design basis accidents;

- Electrical concepts/Emergency Power supply arrangements;

- Control rod drives/Shutdown systems.

For systems training, during the early stages of initial operator training, the simulator training can focus on procedural use during routine operations, such as plant start-ups and shut downs, plant line up during particular modes of operation, taking plant items (e.g. motors or pumps) in and out of service in a controlled manner, etc.

- Teamwork including leadership, roles and responsibilities, communications, procedural use and adherence, decision making including CDM (conservative decision making), ODM (operational decision making), and diagnostics;

- Human factors aspects of operations including; workload management and prioritization, human information processing, shift working and the effects of fatigue/stress on performance, situational awareness and mental models;

- Human Performance practices (HP tools) communications, peer checking, etc.

This event-based training will typically include such topics and scenarios as:

- Events inside and outside of the containment area;

- Reactivity events;

- Abnormal operations (turbine trip, steam leaks, house-load, fire, etc.);

- Loss of the (main) heat sink;

- Steam generator tube rupture;

- Station black-out and subsequent station priorities;

- Earthquake;

- Flooding;

The training should cover a combination of event-based and symptom-based, normal and emergency operating procedures, with severe accident mitigation guidelines training being built into the program.

From the analysis and resulting task-to-training matrix comes the identified objectives, allowing the training program to be designed to form the multiple year curriculum described earlier.

As well as covering the theoretical lessons and practical scenarios, instructors should add local, company/facility, national and international operating experience, along with eventual plant and procedural changes brought to the attention of the program owners since the last review to be considered for future training.

The review of the exercise should accomplish the following:

- Reinforce good behaviors, practices, skills and knowledge observed and gained during the training;

- Recognize and highlight improvement/progress and good performance;

- Reinforce a conservative approach to reactor safety and control;

- Identify trainee and team performance weaknesses and provide guidance on training to correct these weaknesses;

- Correct observed trainee misconceptions;

- Review the accomplishment of position specific learning objectives;

- Facilitate self-evaluation practices of performance by the trainees;

- Review and summary of the objectives and any other learning points that may have come out as a result of the exercise;

- Review and discussion of questions asked during the exercise, including during the debrief and the provision of the correct answers;

- Identification of any procedure improvements identified and owner of update;

- Identification of any plant policy clarification needed and responsible person to pursue and provide update;

- Identification of any simulator improvements noted during training and reporting process to ensure follow up by identified individual post training.

The integration of VR and AR technologies in this approach facilitates both training and certification.

Data from virtual simulations can be used for objective competence assessment - for example, to measure reaction time in an accident, accuracy in performing procedures, or team communication under stressful conditions.

These indicators allow a personalized profile to be built for each operator, identifying the strengths and weaknesses in their training (Chen et al., 2009) [6].

Also, the application of modern technologies contributes to improving safety culture – a key aspect recognized by the IAEA and the World Association of Nuclear Operators (WANO).

Training in a virtual environment encourages open communication, cooperation, and experience sharing among employees, which is fundamental to preventing errors caused by organizational factors [4].

## *5. Practical applications and challenges*

A number of countries have already implemented projects to introduce VR training in nuclear plants. One example is the Finnish company Fortum, which uses virtual environments to train operators at the Loviisa Nuclear Power Plant [7].

The training includes emergency scenarios, equipment replacement, and communication in stressful situations, with all parameters recorded and analyzed in real time.

Despite the obvious advantages, there are also challenges – the high cost of developing VR content, the need to update software, and the need for specialists to adapt curricula to the digital environment.

Therefore, the implementation of these technologies must be strategically planned and integrated into the overall training and qualification program systems, (IAEA, 2020) [4]

## *6. Conclusion*

The application of modern training technologies such as virtual and augmented reality, interactive simulators, and digital twins is a key element in the development of modern staff training at nuclear power plants.

These tools not only improve the quality and effectiveness of training, but also contribute directly to increased safety by minimizing the human factor and improving coordination in real-life situations.

Combining technology and traditional forms of training creates a sustainable training model that supports the development of competent, confident, and responsible personnel - a key guarantee for the safe operation of nuclear facilities.

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