Study on the Effectiveness of Nuclear Simulator-Based Education: A Case Study of the NuScale SMR

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1. Introduction

With the growing need to address climate change and ensure energy security, nuclear power is once again gaining global attention. Small Modular Reactors (SMRs), offering advantages in safety, economics, and flexibility, are emerging as a core next-generation technology. Among them, the NuScale SMR is the only design to have received a Design Certification (DC) from the U.S. Nuclear Regulatory Commission (NRC), and the development of its simulator contributed significantly to validating its design.

Simulators are widely recognized as essential tools for nuclear operator training and qualification, particularly since the Three Mile Island (TMI-2) accident underscored the importance of human error in nuclear safety [1,2]. Following TMI-2, simulator-based team training was institutionalized through the Systematic Approach to Training (SAT), which has become a global standard for nuclear personnel education [3]. Full-scope control room simulators have since been the norm for operator licensing and authorization, supported by both international guidance and national regulations [4-6].

However, existing research and educational programs have largely focused on full-scope simulators for large-scale nuclear power plants, which are designed for the training of licensed operators in complex control room environments [7-8]. In contrast, relatively little attention has been paid to the use of simplified simulators, such as those based on SMR designs, for novice learners in academic settings. This study addresses this gap by analyzing the educational effectiveness of the NuScale SMR simulator at Seoul National University, supported by the Intercollegiate Initiative for Talent Development (IITD). The program is evaluated both quantitatively and qualitatively to assess its impact on students' engineering competencies and to discuss implications for SMR-focused nuclear education.

2. NuScale Simulator

The NuScale Simulator, officially named the Energy Exploration (E2) Center, is based on the NuScale US600 design. Currently, 11 E2 Centers are installed worldwide, serving as key platforms for nuclear education and training. Its main features can be summarized as follows [9-11] :

A. Simplified System Design

With a modular architecture and passive safety systems, the NuScale SMR has a simpler configuration than large-scale plants. This helps novice learners more easily understand the basic principles of reactor operation and safety.

B. Intuitive and User-Friendly Interface

The fully digital control environment provides clear and intuitive displays. Navigation resembles that of common computer or mobile interfaces, lowering the entry barrier for beginners and enabling them to focus on applying knowledge.

C. Educational Accessibility

As a PC-based simulator, the E2 Center is more cost-effective than conventional hardware simulators, allowing broader access. Students can repeatedly practice normal and accident scenarios in a safe setting, strengthening problem-solving skills.

D. Innovative Features

Key functions include a digital procedure library, tiered notification system, integrated emergency procedures, and automated operational sequences, all of which enhance training realism and reduce error potential.

E. Multi-Module Environment

The simulator models a 12-unit NuScale plant. Each workstation allows operators to oversee all modules, providing students with hands-on experience of integrated multi-unit operations and advanced control room practices.

3. Educational Program Overview and Analysis Method

Since March 2024, Seoul National University has operated a NuScale SMR simulator training program with support from the Intercollegiate Initiative for Talent Development (IITD). The program was designed as a two-day course (approximately eight hours in total) that combined theoretical lectures with hands-on simulator exercises. The curriculum included the following:

- Basic SMR design concepts: integral primary system configuration and passive safety systems
- Simulator characteristics: system monitoring, display configurations, and use of digital procedures
- Malfunction scenarios and responses: small-break loss-of-coolant accident (LOCA), main steam line

break (MSLB), anticipated transient without scram (ATWS), and accident management strategies

- Power maneuvering procedures: load-following operations and power ramping
- Startup and turbine synchronization procedures

A total of 131 students participated in the program (95 male, 36 female), ranging from undergraduate freshmen to graduate students and representing diverse academic majors.

To evaluate the program's effectiveness, a pre- and post-training survey was conducted using an experimental and practical competency measurement tool for engineering students [12] This tool measures five domains of competency—Professional Knowledge, Design & Operation, Problem-Solving, Challenge, and Social Contribution—using 30 items on a 5-point Likert scale.

4. Analysis of Educational Effectiveness and Discussion

4.1. Quantitative Results: Competency Change Analysis

Table I: Pre- and Post-Training Competency Scores of Students

Competency Area	Pre-Training Mean (SD)	Post-Training Mean (SD)	t-value	p-value
Professional Knowledge	3.19 (.56)	3.72 (.68)	10.795	<.001
Design & Operation	3.23 (.64)	3.83 (.65)	9.904	<.001
Problem-Solving	3.41 (.51)	3.89 (.65)	8.987	<.001
Challenge	3.79 (.57)	4.12 (.63)	6.086	<.001
Social Contribution	4.04 (.64)	4.28 (.54)	4.801	<.001

The average scores in all competency areas increased significantly ($p < .001$) after the training, clearly demonstrating the positive impact of simulator-based education on students' engineering competencies.

- For Professional Knowledge, the simulator's integrated system visualization enabled students to better understand system-wide interactions rather than fragmented components.
- For Design & Operation, real-time feedback and repetitive practice enhanced the ability to apply operating procedures and technical skills.
- For Problem-Solving, training in abnormal and emergency scenarios provided realistic opportunities to diagnose issues and develop solutions.
- For Challenge and Social Contribution, exposure to high-risk conditions in a safe environment fostered stronger awareness of nuclear safety and reinforced students' motivation to contribute to future energy solutions.

4.2. Qualitative Results: Student Feedback Analysis

Qualitative feedback indicated strong student engagement. Participants emphasized the value of hands-on simulator experience and the opportunity to apply theoretical knowledge in a realistic context. Students also reported that the training increased their interest in nuclear engineering and motivation for professional development.

At the same time, some perceived limitations were noted. Younger students with limited foundational knowledge found certain parts of the program challenging, and many participants suggested that the training period was too short. These findings suggest that the program was highly effective but could be further improved by offering extended sessions and curricula differentiated by student level.

5. Conclusion

This study demonstrated, both quantitatively and qualitatively, that NuScale SMR simulator-based education can significantly enhance students' engineering competencies. The simulator's simplified design and intuitive interface, compared with conventional full-scope simulators, were particularly effective for novice learners by improving system-level understanding and facilitating learning transfer.

The findings highlight the potential of SMR-focused simulator training as a practical methodology for cultivating future nuclear talent. To strengthen future programs, it is recommended to (1) develop level-specific curricula, (2) extend training duration or introduce more complex scenarios, and (3) consider integrating advanced educational technologies such as VR or AI-based tutoring systems.

Overall, this work provides an academic basis for the continued development of simulator-centered nuclear education tailored to the SMR era.

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