BNL-65671
CONF-981011--

OPERATIONAL SAFETY ENHANCEMENT OF SOVIET-DESIGNED NUCLEAR REACTORS VIA DEVELOPMENT OF NUCLEAR POWER PLANT SIMULATORS AND TRANSFER OF RELATED TECHNOLOGY[a]

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ABSTRACT

The United States Department of Energy (U.S. DOE), under the U. S. government's International Nuclear Safety Program (INSP), is implementing a program of developing and providing simulators for many of the Russian and Ukrainian Nuclear Power Plants (NPPs). Pacific Northwest National Laboratory (PNNL) and Brookhaven National Laboratory (BNL) manage and provide technical oversight of the various INSP simulator projects for DOE. The program also includes a simulator technology transfer process to simulator design organizations in Russia and Ukraine. Training programs, installation of new simulators, and enhancements in existing simulators are viewed as providing a relatively fast and cost-effective technology transfer that will result in measurable improvement in the safety culture and operation of NPPs. A review of this program, its present status, and its accomplishments are provided in this paper.

I. INTRODUCTION

One of the key elements that determines the operational safety of a Nuclear Power Plant (NPP) is the training and technical knowledge of its reactor operators about the behavior of their plant. It is widely recognized that simulators play an essential and extremely important role in establishing viable training programs for NPPs. *Full-scope* and *analytical* simulators provide such training tools for reactor operators. The scope of the simulation models is the same for both types of simulators. A full-scope simulator provides control panels that replicate the actual control room panels, as the interface between the operators and the simulation computer. The analytical simulators use personal computers as the interface between the operator and the simulation computer. These tools are used to train the reactor operators in normal and off-normal operations, as well as in training for responding to emergency and accident situations.

The objective of the International Nuclear Safety Program is a comprehensive improvement in safety of Soviet-designed NPPs. This is planned to be accomplished via improvements in: the safety culture of NPP staff and management, power plant operation, physical condition of the power plants and equipment, and infrastructures in countries operating the Soviet-designed reactors. The development and installation of full-scope and analytical simulators help achieve this goal via:

(a) training reactor operators on the installed simulators and thus improving the safety of power plant operation directly, and

(b) improving the safety culture of NPP staff by interaction with the U.S. participants during simulator development, technology transfer, and training.

II. SIMULATOR DEVELOPMENT PROGRAM

A. An Overview

A summary of simulator programs in Russia and Ukraine is given in Table 1. The Khmelnytskyy full-scope simulator and the Chornobyl analytical simulator have recently been completed and declared Ready For Training.

[a]This work was performed under the auspices of the U.S. Department of Energy.

The Novovoronezh analytical simulator is expected to be completed by July 1998. Other projects are on-going.

The simulator development program provides the basis for the development and installation of the latest advances in simulation technology at the Russian and Ukrainian NPPs. This includes advanced three-dimensional thermal-hydraulic simulation of the primary system for a VVER-1000 reactor, advanced neutronic models for the reactor core, and complex system malfunction models.

To avoid the occurrence of negative operator training, a very high degree of simulator fidelity (to the reference plant) is required. A key element for the achievement of simulator fidelity is the use of a Verification and Validation (V&V) methodology during the design, development, and testing of the simulator. This process must be implemented by knowledgeable plant personnel. General Physics Corporation assisted BNL and PNNL in the development of a training workshop to provide V&V methodology training to the staff of Russian and Ukrainian NPPs. The training workshop covered the following major topics: experience of US utilities in Verification and Validation of full-scope simulators, verification tasks during procurement of simulators including documentation for Verification and Validation, regulatory requirements, human factors connected with simulator fidelity during testing, methodology for validation of simulators, evaluation of acceptance test results, and a step-by-step Verification and Validation procedure.

The first week-long V&V workshop was presented at the Khmelnytskyy NPP in Ukraine during July 1997. Participants included staff from the Khmelnytskyy, Chornobyl, and South Ukraine NPPs, and from the Engineering Technical Center (ETC) on Personnel Training for Nuclear Energy in Kyiv, Ukraine. The second workshop was presented at the facilities of the Russian simulator vendor, VNIIAES, in Moscow in April 1998. The workshop participants were particularly interested in the relationship between US-NRC and the US NPPs, especially with regard to initial certification and maintenance of the simulator.

B. The Ukrainian Simulator Projects

1. Khmelnytskyy Full-Scope Simulator. In November 1994, under the Lisbon Nuclear Safety Initiative, a contract was awarded to GSE Systems (originally S3 Technologies) for the development and installation of a full-scope simulator for the Khmelnytskyy Nuclear Power Plant (KhNPP) in Neteshin, Ukraine. The plant is a 1000 MWe VVER system which had begun commercial operation seven years before. It successfully passed the Site Acceptance Test during December 1997 and has been declared Ready for Training. This project represents the first joint venture of this nature between the United States and Ukraine. It was also used as a vehicle for a separate project for simulator technology transfer to Ukraine where approximately twenty staff members from the Khmelnytskyy NPP and the ETC spent about one year at the simulator vendor's site in the U. S.. During the course of this technology transfer project, the Ukrainian staff worked with the vendor's staff and participated in the design, development, and construction of the Khmelnytskyy full-scope simulator, and development of acceptance test procedures and simulator training scenarios. In addition to the Khmelnytsky NPP staff, the ETC staff also participated in the acceptance testing of the full-scope simulator. They also received training in simulator hardware and software maintenance. This simulator represents the first installed simulator in Ukraine which contains modern simulator hardware and software, and which utilizes the latest simulation techniques.

2. Chornobyl Unit 3 Analytical Simulator. After preparation of the Technical Specification document for this simulator, a contract for the development and installation of the simulator was awarded to GSE in August 1996. This contract specified that an existing RBMK simulation model, similar to the Chornobyl NPP, be used as a basis for the initial simulation model. This model selection was intended to leverage the modeling of existing RBMK simulators, expedite the delivery of the Chornobyl simulator, and provide financial resources for other aspects of the project.

Early in the project, a two-week training course for the Chornobyl NPP technical staff was completed at the BNL in the use of the computer software utilized in simulators. This initial training was followed by a training program provided by the simulator vendor. Three members of the Chornobyl NPP technical staff participated in this training.

Final acceptance testing of this simulator was completed at the Chornobyl NPP site in December 1997, and the simulator was declared Ready for Training.

3. South Ukraine Unit 3 Full Scope Simulator. A Memorandum of Understanding (MOU) between the U.S. side and the Ukrainian side for this project was signed in October 1995. Under the terms of the MOU, this project was conceived as a joint US-NPP funded project. The U.S. side was to provide funding for the procurement of the Computer Complex (simulation, instructor station, development, and plant process computers) hardware and software, Input/Output (I/O) System (interface between the simulation computer and the control panel hardware), Power Distribution Center (PDC), and training of the NPP staff.

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The South Ukraine NPP was to provide funding for the control panels and instruments, simulator software models, assembly and integration of all hardware and software, and acceptance testing of the simulator. Virtually all of the US-funded tasks (including the software training of NPP staff) have been completed. However, due to acute financial difficulties experienced by the South Ukraine NPP, the NPP has only funded the task of control panel construction. Whereas all the control panel structures have been fabricated, only about 50% of the control panel instruments have been procured. In October 1997, the U.S. side agreed to fund all the remaining tasks for the completion and installation of the full-scope simulator. A contract for these tasks is expected to be placed with the simulator vendor by July 1998. It is anticipated that this full-scope simulator will be ready for training by September 1999.

4. South Ukraine Unit 1 Full Scope Simulator. Like the South Ukraine Unit 3 project, this project was also to be a joint US-NPP funded project. An MOU for this project was signed in April 1996. However, due to the financial difficulties of the South Ukraine NPP, the NPP has been unable to fund any of the tasks for simulator development. As a result, the completion of this project has been delayed, and consequently in February 1998, the U.S. side agreed to fund all the tasks for simulator development. A contract for the tasks that were originally the responsibility of the South Ukraine NPP is expected to be placed with the simulator vendor by July 1998. The following tasks have been completed:

- Computer Complex hardware and software procured and tested
- PDC and the Uninterruptible Power Supply (UPS) manufactured and tested
- Data collection for the control room hardware
- Instrument and Control (I&C) design

It is anticipated that this full-scope simulator will be ready for training by December 2000.

5. Rivne Unit 3 Full Scope Simulator. This project is very similar to the South Ukraine Unit 1 project in terms of the original responsibilities of the U.S side and Rivne NPP, and both of these projects started at the same time. The Rivne NPP has been no exception to the typical financial difficulties experienced by virtually all Ukrainian (and Russian) NPPs. Consequently, it has been able to fund only the construction of control panel structures (without any instruments), and will not be able to fund any of the other tasks that it was to have funded for the development and installation of the full-scope simulator. In February 1998, the U.S. side agreed to fund all the remaining tasks for the development and installation of the full-scope simulator at the Rivne NPP. A contract for these additional tasks is expected to be placed with the simulator vendor by July 1998. The following tasks have been completed:

- Computer Complex hardware and software procured and tested
- PDC and the UPS manufactured and tested
- I&C data base collection

It is anticipated that this full-scope simulator will be ready for training by December 2000.

6. Zaporizhzhya Unit 5 Full Scope Simulator. The purpose of this project is to provide support for upgrading the existing full-scope Simulator for the Zaporizhzhya Unit 5 NPP. Among other items, the simulator Computer Complex, simulator core neutronics and thermal-hydraulic models, and the Turbine Control System need to be upgraded. An MOU between the U.S. side and the Ukrainian side for this project was signed in February 1997 and the contract for U.S. funded tasks was awarded in September 1997. The upgrade is scheduled to be completed by May 1999.

C. The Russian Simulator Projects

1. Novovoronezh Analytical simulator. Since the Novovoronezh site did not have a simulator at the plant when this project was initiated, the objective of this project was to provide the Novovoronezh NPP with an analytical simulator for Unit 3, a 400 MWe VVER nuclear reactor. Following the preparation of the Technical Specification document for this simulator, a contract for the development and installation of the simulator was awarded to the simulator vendor in August 1996. The development of the simulator models is complete and currently the simulator is undergoing final acceptance testing. During a few of these tests some difficulties in plant cool down — specifically oscillations during phase transfer processes were encountered. These difficulties were, however, successfully resolved. The simulator, which is scheduled to be declared ready for training in July 1998, will be the first modern simulator for a VVER 440 plant in Russia. During the course of this project, training in hardware and software maintenance, and specialized instruction to help NPP personnel train new operators, was provided to the Novovoronezh NPP staff.

2. Kola Unit 4 Full-Scope simulator. The MOU for this jointly funded (by the U.S. side and the Kola NPP) project was signed in July 1995. Subsequently, contracts for various simulator development tasks were placed with the simulator vendors. The following tasks have been completed:

- Procurement and testing of the Computer Complex
- Manufacture of PDC, UPS, and the I/O System

The construction of the control panels and instruments is in progress and is expected to be completed by June 1998. Simulator model development is continuing and the simulator is expected to be declared ready for training by June 1999.

3. Kalinin Unit 2 Full-Scope Simulator. An MOU between the U.S. side and the Russian side for this project was signed in July 1995. While the U.S. side was to provide funding for the Computer Complex, PDC, UPS, I/O System, and advanced thermal-hydraulic and core neutronics models, the Kalinin NPP was to provide funding for (among other items) the Control Panel hardware including instruments, simulator models (software) not funded by the U.S. side, assembly and integration of all hardware and software, and acceptance testing of the simulator. The contracts for U.S. funded tasks were placed in 1995 and 1996. In October 1996 the Russian side informed the U.S. side that due to financial difficulties of Kalinin NPP, the NPP is not able to fund the construction of both the control panel structures and the panel instruments. As a result, to prevent project delays the U.S. side agreed to fund the construction of control panel structures while the Kalinin NPP was to fund the manufacture of the panel instruments. To date the following U.S. funded tasks have been completed:

- Procurement and testing of the Computer Complex
- Manufacture of PDC, UPS, and the I/O System
- Development of advanced three-dimensional thermal-hydraulic and core neutronics models
- Construction of control panel structures (without the instruments)

The three-dimensional thermal hydraulic and core neutronics models have been integrated with the Balance of the Plant. The three-dimensional effects can clearly be seen in transients like the Reactor Coolant Pump trip. These effects have been indirectly validated by comparison to limited plant data.

Due to the inability of the Kalinin NPP to provide funds for the control panels and instruments, the progress of the project was interrupted because none of the remaining tasks could be finished without the instrumented panels. The U.S. side has recently agreed to fund the procurement of control panel instruments, and after a contract for this task is awarded, this project will continue.

4. Balakovo Simulators. The INSP program is providing the Balakovo NPP Training Center with two systems, in order to improve and expand their capability to train their NPP operator staff. An Analytical Simulator is being procured to expand the Training Center's capability, and an upgrade of the existing Full-Scope Simulator is being developed to improve its simulation capabilities. The Full-Scope Upgrade portion of the project will include installation of Standby Control Room Panels, and integration with the simulator models. Both simulators will be provided with identical, new, upgraded simulation models of the Balakovo NPP, Unit 4. These models will include the upgraded Turbine Control System. The Plant Process Computers will also be replaced and will be provided with upgraded software. Training of Balakovo staff in operation of the new and upgraded simulators will be provided. The two projects involve both hardware and software procurements, and acceptance testing.

A program plan for the project has been developed. The computer hardware for both the Analytical Simulator and the Full-Scope Simulator Upgrade has been purchased, tested, and shipped to Russia. The Database Report has been assembled from NPP documentation, and it has been reviewed and accepted by the Balakovo NPP. Specifications for the Uninterruptible Power Supplies for both simulators have been written.

Simulator model development is underway. The Analytical Simulator is scheduled for completion in January 1999. Completion of the Full-Scope Simulator Upgrade project is scheduled for July 1999.

5. Bilibino Analytical Simulator. The Bilibino nuclear plant is of a unique design, comprising four identical units, each capable of generating 12 MW of electrical output as well as 20 MW of heat. It is a graphite-moderated natural circulation driven reactor. A contract for the development and installation of an analytical simulator for this NPP was awarded in September 1997 to GSE Power Systems. Most of the modeling effort for this simulator will be performed by GSE's subcontractor, LAKROM, in Moscow. Formal classroom training in hardware and software maintenance, as well as specialized training for simulator instructors, will be provided to the Bilibino NPP staff. Data collection for the simulator has been completed and the simulator

Computer Complex has been procured. Model development for the simulator is continuing, and the simulator is scheduled to be ready for training by December 1999.

III. PROBLEMS ENCOUNTERED AND LESSONS LEARNED

A number of lessons were learned from the interaction among the U.S. side, the U.S. simulator vendor, the Russian simulator vendors, the Ukrainian vendors, and the NPPs. The problems encountered were generally a result of cultural differences — or differences in the way things are seen and done (corporate behavior) in Ukraine/Russia versus the United States. In addition, the meager fiscal resources of the NPPs contributed to their own sets of problems. Four examples from the Khmelnytskyy project illustrate specific issues that resulted in project delays and additional costs.

(1) Data Collection - It was agreed at the beginning of the project that relevant plant data would be provided by the plant to the model developers. Although this was partly adhered to, the initial process for the transfer of information was difficult to implement, leading to data collection delays.

(2) Provision of Panels/Instruments - The plant was committed to providing control panels (which were to be salvaged from an actual unit that had been canceled) together with the appropriate panel instruments. Largely because of the unexpected physical condition of the panels and instruments, additional funds had to be allocated in order to modify the panels and provide the instruments.

(3) Customs Problems - Even though the agreements connected to this program provided for duty-free and expeditious entry into Ukraine of materials needed for the simulator, the implementation of these arrangements did not materialize until detailed procedures and new protocols were negotiated. This led to delays and unnecessary expenses, particularly regarding hardware meant for the construction of the panels.

(4) Building Delays - One contribution of the Ukrainian side was the construction of the Training Center Building to house the simulator complex. Although this was eventually accomplished, the building construction was slowed down by many unanticipated factors, such as, lack of resources, weather and changes in contractors and crews. It eventually resulted in delays in subsequently scheduled activities, with the attendant effects on time and budgets.

Completing the control panels and instrumentation for the simulator is a very difficult task due to the fact that, in most cases, there is only a single supplier for the instruments for the Soviet-designed reactors. On the positive side, largely due to the resourcefulness of the simulator vendor, the Khmelnytskyy project delays were limited to only three months. In addition, the technology transfer was quite useful for the power plant personnel who were subsequently able to practice their newly learned skills at the plant and the simulator.

A brief summary of some of the lessons learned is given below:

- *The importance of having a Memorandum of Understanding.* The entire simulator procurement and development process is a new experience for the Russian and Ukrainian NPPs (recipient). The open dialog and discussion during development of such an agreement provides an excellent opportunity for both sides to clarify and mutually understand their roles and responsibilities. Even though problems may occur with implementation, it is much clearer what needs to be done to resolve a problem and minimize costs and delays.

- *Involving the recipient in the review and acceptance of all project documentation.* While simulator technology is new to the recipient, it is important that they participate in the development and/or review of technical specifications, vendor proposals, preliminary and final design documents, and the acceptance test program.

- *Frequent and open communications are important.* Discussions with the recipient during planned meetings at key project milestones are not sufficient. Plans often need to be altered due to changes in customs requirements, the availability of in-country resources and supplies, and the economic situation. It is prudent not to assume that all things will happen as planned, and therefore everything needs to followed up regularly. It is important to keep options open and plan for contingencies.

- *Involvement of NPP operators during simulator development and testing.* It is critical that the senior plant management understands the importance of providing some of their best operators to develop acceptance test procedures and serve as test operators. Plant data is not always available and expert knowledge of plant components, systems and operation is essential.

- *Coordination with other training programs.* It is beneficial to coordinate the simulator development with other training program activities, such as the development of simulator exercise guides and training materials. A training system and staff need to be in place to ensure effective utilization of the simulator when it is completed.

- *Having technically knowledgeable interpreters.* Interpreters that are familiar with the technical terminology are essential during discussions and meetings with the recipient. In addition, using the same interpreters on all projects also leads to improved understandings and consistency. With good interpreters many potential misunderstandings will be avoided.

IV. ACCOMPLISHMENTS AND CONCLUDING REMARKS

A full-scope simulator for the Khmelnytskyy NPP and an analytical simulator for the Chornobyl NPP have been successfully completed and declared Ready for Training. The analytical simulator for the Novovoronezh NPP is expected to be completed by July 1998.

The U.S., in coordination with other Western countries, is in the process of providing or supporting training simulators in Russia and Ukraine. It is expected that access to NPP simulators will provide the following benefits:

- Improved training of NPP staff in normal and off-normal operations, and during accident and emergency scenarios.

- Improved overall and system-level understanding of NPP operating characteristics on the part of reactor operators.

- Development and validation of Emergency Operating Instructions (EOIs).

- Improved analytical capabilities of the NPP technical support staff.

- Development and implementation of training programs based on simulators.

- Establishment of host country capabilities to design and manufacture full-scope and analytical simulators for NPPs.

At the completion of these programs all Russian and Ukrainian NPP sites having VVER-type nuclear power plants will have either a full-scope or analytical simulator in place to provide enhanced training capabilities to their operators, thereby resulting in increased plant safety. The future challenge is to ensure that the training facilities in Russia and Ukraine maintain their simulators in a certifiable state and continue to impart the highest standard of training possible, thus ensuring an increased level of safe operation for Soviet-designed NPPs.

V. ACRONYMS

BNL Brookhaven National Laboratory

DOE Department of Energy

ETC Engineering Technical Center on Personnel Training for Nuclear Energy, Kyiv, Ukraine.

INSP International Nuclear Safety Program

MOU Memorandum of Understanding

NPP Nuclear Power Plant

PDC Power Distribution Center

PNNL Pacific Northwest National Laboratory

UPS Uninterruptible Power Supply

VNIIAES Russian Institute for Nuclear Power Plant Operations (Russian simulator vendor), Moscow, Russia

VVER Soviet-designed pressurized water reactor

Table 1. Summary of INSP simulator projects in Russia and Ukraine

NPP	Simulator Type	Funding	Lead Vendor
Balakovo Unit 4 VVER-1000	Analytical, Full-scope upgrade	U.S.	GSE/VNIIAES
Bilibino	Analytical	U.S.	GSE/VNIIAES
Chornobyl Unit 3 RBMK	Analytical	U.S.	GSE/VNIIAES
Kalinin Unit 2 VVER-1000	Full-Scope	U.S./NPP	VNIIAES/GSE
Khmelnytskyy VVER-1000	Full-Scope	U.S.	GSE
Kola Unit 4 VVER-440	Full-Scope	U.S./NPP	VNIIAES/GSE
Novovoronezh Unit 3 VVER-440	Analytical	U.S.	GSE/VNIIAES
Rivne Unit 3 VVER-1000	Full-Scope	U.S./NPP	GSE
South Ukraine Unit 1 VVER-1000	Full-Scope	U.S.	GSE
South Ukraine Unit 3 VVER-1000	Full-Scope	U.S./NPP	VNIIAES/GSE
Zaporizhzhya Unit 5 VVER-1000	Full-Scope Upgrade	U.S.	GSE/VNIIAES

Notes: GSE: U.S. simulator vendor, VNIIAES: Russian simulator vendor