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U.S. DEPARTMENT OF ENERGY SPONSORED IN-DEPTH SAFETY ASSESSMENTS OF VVER AND RBMK REACTORS

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ABSTRACT

Throughout the 1990s the National Nuclear Security Administration of the U.S. Department of Energy has worked to build capability in countries of the former Soviet Union to assess the safety of their VVER and RBMK reactors. Through this Plant Safety Evaluation Program, deterministic and probabilistic analyses have been used to provide a documented plant risk profile to support safe plant operation and to set priorities for safety upgrades. Work has been sponsored at fourteen nuclear power plant sites in eight countries. The Plant Safety Evaluation Program has resulted in immediate and long-term safety benefits for the Soviet-designed nuclear plants.

INTRODUCTION

Since the disastrous accident at Chornobyl Nuclear Power Plant Unit 4 in 1986, there has been international recognition of the safety concerns posed by the operation of 69 Soviet-designed commercial nuclear reactors (table 1). These reactors are operated in eight countries from the former Soviet Union and its former satellite states in Central and Eastern Europe. The majority of these plants are in the Russian Federation (30 units) and Ukraine (13 units). New plants are in various stages of construction.[1, 2]

Table 1. Soviet-Designed Reactors in Operation

Country	Reactor Model	Country	Reactor Model
Armenia	1 VVER-440/270	Russia	2 VVER-440/179 2 VVER-440/230 2 VVER-440/213 7 VVER-1000 11 RBMK-1000 4 LWGR 1 VK-50 1 BN-600
Bulgaria	4 VVER-440/230 2 VVER-1000		
Czech Republic	4 VVER-440/213 1 VVER-1000		
Finland	2 VVER-440/213	Slovakia	2 VVER-440/230 4 VVER-440/213
Hungary	4 VVER-440/213	Ukraine	2 VVER-440/213 11 VVER-1000
Lithuania	2 RBMK-1500		

On the whole, the infrastructure in countries deploying Soviet-designed VVER and RBMK reactors has not exhibited the characteristics of a healthy safety culture. In particular, attention was not paid to developing the requirements, tools, and methodologies to assess and identify the safety basis of the facilities and any related deficiencies. Furthermore, the plant operators and regulators had not been provided with the tools and information needed to accurately determine the safety condition of the plants. That is to say, technical safety information was not openly exchanged in the Soviet system. Compounding this problem was the technical isolation of the former Soviet Union countries that did not allow for open international technical interaction. There is general consensus today that these issues were underlying causes of the Chornobyl disaster.

U.S. support to improve the safety of Soviet-designed reactors over the past decade has been intended to increase operational safety, provide for risk-reduction measures, and enhance regulatory capability. The U.S. approach to improving the safety of Soviet-designed reactors has matured into a large multi-year program known as the Soviet-Designed Reactor Safety Program that is managed by the National Nuclear Security Administration (NNSA) of the U.S. Department of Energy (DOE). The mission of the program is to implement a self-sustaining nuclear safety improvement program that would lead to internationally accepted safety practices at the plants. Those practices would create a safety culture that would be reflected in the operation, regulation, and professional attitudes of the designers, operators, and regulators of the nuclear facilities. A key component of this larger program has been the Plant Safety Evaluation Program, which supports in-depth safety assessments of VVER and RBMK plants.

The 1979 accident at the Three Mile Island power station signaled the start of a massive effort in the U.S. and other Western nations utilizing nuclear power to revamp their approach to nuclear safety. The lessons learned from this accident have had a large effect on U.S. nuclear power plant operation and regulation. The most important lessons came from analyzing the events leading up to the accident and assessing actions that could have been taken to prevent such serious damage to the reactor core. The lessons of the Three Mile Island accident have had a profound effect on the manner in which nuclear safety is considered in nuclear power plant operation.

In contrast to the evolution of safety concepts in the West, at the time of the 1986 accident at Chornobyl Nuclear Power Plant Unit 4 in-depth information of Soviet-designed reactor design and performance was unavailable at the plants. Power plant staff knowledge of plant design was mostly restricted to operational limits and operating procedures developed elsewhere. It is now generally recognized that this lack of understanding at the plant about the plant's design and operation was a major contributor to the Chornobyl accident. The parallels to the root causes of the Three Mile Island accident are clear in that in both cases the operators were unprepared to deal with the events that were unfolding and had an incomplete understanding of the plant's design basis.

With the breakup of the Soviet Union, an opportunity was presented to address the technical isolation experienced by operators of Soviet-designed reactors. Consistent with the lessons learned in the West, the NNSA Plant Safety Evaluation Program has supported the development and understanding of a safety basis at the plants that provides the technical underpinning for improving and sustaining safer operation of Soviet-designed reactors.

NNSA PLANT SAFETY EVALUATION PROGRAM

Support of in-depth safety assessments is the heart of the Soviet-Designed Reactor Safety Program's Plant Safety Evaluation efforts. Through this program, the NNSA promotes the safe operation of Soviet-designed reactor facilities through the transfer of knowledge and technology to the host countries so that they obtain the capability to take responsibility for safety assessments with guidance from Western experts. The NNSA provides technical and financial assistance to plant operators and their technical support organizations. The scope of support varies among the projects, depending on the site-specific needs for probabilistic and deterministic technologies.

In-depth safety assessments consist of deterministic, probabilistic, engineering, and institutional studies assessing operational Soviet-designed nuclear power units in the context of local regulations. The in-depth safety assessment process is similar to the more complex and extensive safety analyses required for Western commercial nuclear facilities.

The main objectives of in-depth safety assessments for Soviet-designed plants are

- to reflect the true safety status of the unit;
- to show whether the technical condition of the structures, systems, and components of the power plant ensures the safe operation of the unit;
- to reveal possible deviations from the requirements of the existing rules and regulations and to justify the adequacy and effectiveness of the compensatory measures taken;
- to determine whether the operating procedures carried out at the plant, the administrative management, official inspection arrangements, and the quality assurance system enable the operator to ensure the safe operation of the unit; and
- to determine whether the effects of the operation of the unit on the plant personnel, the public, and the environment exceed the safety limits established by the rules and regulations.

A number of in-depth safety assessment joint projects are being carried out at selected nuclear power plants in countries of the former Soviet Union. The objective of these projects is to provide a documented plant risk profile to support safe plant operation and to provide justification for proceeding with appropriate safety upgrades. Plant staff lead the in-depth safety analysis projects and subcontracted host-country technical support organizations perform various technical activities. Western experts provide on-site technical mentoring and management assistance. Plant ownership of the in-depth safety assessment is necessary to guarantee the long-term application of high quality analyses to decisions regarding the operation of the plant. The development of safety analysis capability at the technical support organizations builds infrastructure that can continue to aid the safety analysis needs of the plant. Moreover, that capability will be invaluable to the assessment of nuclear power facilities not currently part of the Plant Safety Evaluation Program.

To date, the Plant Safety Evaluation Program has sponsored work at fourteen nuclear power plant sites in eight countries representing several Soviet reactor designs (table 2). The immediate safety needs were seen to be different at each plant, so the specific safety analysis tasks performed has varied from plant to plant. Those task choices have been based largely on Western expert judgment of nuclear plant safety needs. As in-depth safety assessment results become more available, more informed decisions can be made as to the priorities of analyses and system upgrades.

Of particular importance has been the support provided for level 1 internal-event probabilistic risk assessments. With resources provided by the NNSA, Western Europe, and the host countries, probabilistic risk assessments are now available for several plants, including Novovoronezh Unit 3 (VVER-440/230), Bohunice Units 1 and 2 (VVER-440/230), Kola Unit 4 (VVER-440/213), Rivne Unit 1 (VVER-440/213), Novovoronezh Unit 5 (VVER-1000/187), South Ukraine Unit 1 (VVER-1000/203), Zaporizhzhya Unit 5 (VVER-1000/320), and Leningrad Unit 2 (RBMK-1000). A level 1 risk assessment for Kola Unit 2 (VVER-440/230) should be completed later this year. Comparison of these studies is underway to search for inconsistencies in risk assessment modeling, to identify generic design and operational weaknesses, and to communicate to plant operators successful corrective measures to reduce risk.

FINDINGS OF THE PLANT SAFETY EVALUATION PROGRAM

The NNSA Plant Safety Evaluation Program has resulted in three types of safety benefits: immediate benefits from addressing in-depth safety assessment findings, near-term operational benefits based on the plant knowledge gained through in-depth safety assessments, and benefits in making informed management decisions based on acquired safety knowledge.

Table 2. NNSA-Sponsored Safety Evaluation Work

Country	Plant	Work Scope
Armenia	Armenia	Deterministic analyses
Bulgaria	Kozloduy	Deterministic analyses; international assessment of thermohydraulic codes
Czech Republic	Dukovany	Probabilistic analyses; severe accident management
Hungary	Paks	Hydrogen mixing analyses for loss of coolant accidents
Lithuania	Ignalina	Integrity analyses for piping and structures; international assessment of coupled codes
Russia	Kola Kursk Leningrad Novovoronezh	Deterministic and probabilistic analyses; international assessment of neutronic and thermohydraulic codes
Slovakia	Bohunice	Deterministic analyses; human reliability analyses
Ukraine	Khmelnytskyy Rivne South Ukraine Zaporizhzhya	Deterministic and probabilistic analyses; international assessment of neutronic and thermohydraulic codes

In many cases the in-depth safety assessments identify system weaknesses that are unique to the plant being evaluated. For example, internal-event probabilistic risk assessments have demonstrated that small loss-of-coolant accidents are the dominant initiating event for the Kola and South Ukraine plants evaluated, but are a comparatively small relative contributor to the core damage frequency for Novovoronezh Unit 5. Novovoronezh Unit 5 has unique design features (such as the location of the fast-acting isolation valves) that contribute to the relative importance of different initiating events to the core damage frequency. These findings illustrate the importance of performing plant-specific safety assessments rather than ones based on generic plant design information.

Often the value of in-depth safety assessments extends beyond the plant being evaluated in that generic design weaknesses can be identified. For instance, though its relative importance with respect to other initiating events varies among the different plants, loss of off-site power has been found to be a significant contributor in all the probabilistic risk studies. It represents about 10% of the core damage frequency contribution in the VVER-1000 units and a larger contribution (20%-30%) in the VVER-440 units. Hardware modifications can help reduce this risk.

Application of modern in-depth safety assessment technology has played an important role in providing important safety insights and understanding of Soviet-designed reactor performance. In particular, probabilistic risk assessment projects yield numerical values that characterize relative plant safety. The results can be used to forecast the affect of proposed changes and to establish improvement priorities to institutional, operational, regulatory, and engineering systems.

Through the in-depth safety assessments of the Plant Safety Evaluation Program, specific design deficiencies and plant vulnerabilities have been identified in each plant examined. Those deficiencies must be addressed to reduce the overall plant risk. Remedial actions have been initiated at the first plants to complete in-depth safety assessments. Progress on the assessments will continue at the other NNSA-supported units.

PROBABLISTIC RISK ASSESSMENT INSIGHTS

Probabilistic risk assessment technology has been shown to dependably assess both VVER and RBMK design features and has provided important safety insights. Probabilistic analyses provide a risk-based way to establish priorities for proposed improvements to institutional, operational, and regulatory systems, in addition to proposed equipment upgrades.

Operator actions have been found to be a large contributor in all the Soviet reactor probabilistic risk studies. For example, operator actions are dominant risk contributors at the South Ukraine, Kola, and Novovoronezh units, where they contribute more than a third of the core damage frequency. In the first two cases, the most significant human error is the potential operator failure to realign the emergency core cooling system during an event. At Novovoronezh Unit 5, the main contributor is the potential failure to prevent the closure of the fast-acting isolation valves. These risks are serious, in part, because of the use of event-based emergency operating instructions rather than symptom-based ones. Developing and implementing symptom-based procedures should dramatically improve safety. These activities are already underway at many plants under the sponsorship of the NNSA Soviet-Designed Reactor Safety Program.

An objective of the Plant Evaluation Program has been to maximize plant involvement in the probabilistic and deterministic modeling. A high level of plant involvement ensures that a cadre of knowledgeable personnel are available with a unique risk-based, integrated-system view of the plant. These experts are essential to incorporating the insights gained on system and component vulnerabilities into plant operation, maintenance, and training activities. It is essential that the personnel responsible for maintaining the probabilistic risk assessment model be involved in plant operation, maintenance, and training. In this way, they are able not only to apply the lessons learned to these activities, but also to ensure that changes in these activities are reflected in revisions to the models.

Ongoing application of the safety assessment analytical tools ensures a sustained benefit from the deterministic and probabilistic model development efforts of the in-depth safety assessment process. These models, however, are valid and useful only if they reflect the current plant configuration. The in-depth safety assessments generally are for a given set of conditions reflecting the plant at some specific point in time. Continued maintenance of the models is necessary if they are to be used at any future date. This maintenance requires a continuing relationship between the technical support organizations and plant staff as well as a formal process to incorporate and document plant configuration changes and insights gained during significant plant events. The NNSA and the international community are sponsoring the development of component reliability and human-factor databases for use at Soviet-designed reactors. These databases will allow the plants to share their reliability data to improve the quality of probabilistic risk assessments at all Soviet-designed reactors.

CONCLUSIONS

At the beginning of the NNSA Soviet-Designed Reactor Safety Program, the safety needs in former Soviet Union countries were so glaring that immediate action was called for to remediate the major concerns. Therefore, initial activities focused on projects judged to yield safety benefits within a year or two, such as upgrades of equipment and implementation of institutional controls. Those judgments, of course, could not rely on local safety insight, but were based on Western safety experience. Meanwhile, projects were undertaken to develop indigenous safety insight through the performance of in-depth safety assessments.

The in-depth safety assessments performed thus far for Soviet-designed power plants have been useful in making first-order appraisals of Soviet-reactor safety. Notably, the results obtained so far do not indicate the need for immediate and permanent plant shutdown. Plant problems have been uncovered, but remediation programs have been quickly implemented to resolve the most grievous issues. At all Soviet-designed plants, substantial upgrades would be required to justify long-term operation. In-depth safety assessment methodologies provide a tool for setting priorities for those improvements.

A significant finding of the NNSA Plant Safety Evaluation Program has been that risks are sensitive to plant-specific designs and configurations. Therefore, the results obtained so far cannot be fully extrapolated to plants yet to be assessed. Moreover, a plant found today to be of low risk may have significant risks as configurations change, components age, safety analysis models are refined, and external events such as floods and earthquakes are considered. There is a need, then, to encourage the completion of in-depth safety assessments at all Soviet-designed reactors and, furthermore, to evolve living design basis documentation and living probabilistic risk assessments to allow a continual monitoring of plant risk.

So long as countries of the former Soviet Union move forward with their plans to continue operation of their Soviet-designed reactors, completion and maintenance of in-depth safety assessments by the plant will provide a quantitative means to implement plant improvements to bring safety to a level appropriate for reliable long-term operation. Sustained safety improvement can be achieved only through developing safety expertise at the plants and strengthening the safety infrastructure. In particular, once obvious deficiencies have been resolved, it becomes more difficult to set priorities for additional improvements. In-depth safety assessments are the logical basis from which to make such decisions, since those assessments can provide a quantified measure of the safety benefit of the choices. Decision making based on Soviet-reactor safety assessments will be especially important as countries evaluate other nuclear units not currently part of the Soviet-Designed Reactor Safety Program. Those plants could immediately benefit from the safety analysis experience of plants of similar Soviet design. In this way, there would be less uncertainty in utilizing limited financial resources to make safety-related decisions. Moreover, decisions about operation beyond the designed lifespan of a plant should incorporate the knowledge gained through safety assessments. In this case, though, additional studies would be needed to account for plant aging and other issues not considered during the designed lifetime.

Several qualitative safety benefits have been born of the NNSA Soviet-Designed Reactor Safety Program:

1. The process of conducting in-depth safety assessments has resulted in an improved safety culture at the plants and in improved communication among the plant, technical support organizations, regulators, and the international nuclear safety community.

2. In-depth safety assessments have provided a mechanism to judge the effectiveness of the near-term safety improvements implemented before assessment results were available.

3. Probabilistic safety assessments demonstrated that operator error is a dominant risk factor at all Soviet-designed plants, thus affirming the early program decision to emphasize operator training, plant simulators, and symptom-based emergency operating instructions.

4. In-depth safety assessments identified generic reactor design concerns that must be addressed. Examples include the vulnerability to fires, the clogging of the recirculation cooling path for VVER units, and concerns for shutdown reliability and primary-system integrity for RBMK units. The resolution of these concerns would have benefits to all Soviet-designed reactors, even those not currently being assessed through the NNSA program.

The U.S. will continue to have collaborative programs with operators of Soviet-designed nuclear power plants as they conduct in-depth safety assessments and address the concerns identified. Incorporation of the insights gleaned from the Plant Safety Evaluation Program will help to ensure safety improvement at the plants will be sustained upon conclusion of the NNSA program.

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