The Role of PRA in the Safety Assessment of VVER Nuclear Power Plants in Ukraine

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DISCLAIMER

ABSTRACT

Ukraine operates thirteen (13) Soviet-designed pressurized water reactors, VVERs. All Ukrainian plants are currently operating with annually renewable permits until they update their safety analysis reports (SARs), in accordance with new SAR content requirements issued in September 1995, by the Nuclear Regulatory Authority and the Government Nuclear Power Coordinating Committee of Ukraine. The requirements are in three major areas: design basis accident (DBA) analysis, probabilistic risk assessment (PRA), and beyond design-basis accident (BDBA) analysis. The last two requirements, on PRA and BDBA, are new, and the DBA requirements are an expanded version of the older SAR requirements.

The US Department of Energy (USDOE), as part of its Soviet-Designed Reactor Safety activities, is providing assistance and technology transfer to Ukraine to support their nuclear power plants (NPPs) in developing a Western-type technical basis for the new SARs. USDOE sponsored In-Depth Safety Assessments (ISAs) are in progress at three pilot nuclear reactor units in Ukraine, South Ukraine Unit 1, Zaporizhzhya Unit 5, and Rivne Unit 1, and a follow-on study has been initiated at Khmenytskyy Unit 1.

The ISA projects encompass most areas of plant safety evaluation, but the initial emphasis is on performing a detailed, plant-specific Level 1 Internal Events PRA. This allows the early definition of the plant risk profile, the identification of risk significant accident sequences and plant vulnerabilities and provides guidance for the remainder of the safety assessments.

The results from the just completed Level 1 Internal Events PRA for South Ukraine Unit 1 validate this approach. Major risk contributors are clearly defined and significant vulnerabilities are identified. The largest contributions to risk came from Loss of Coolant Accidents (LOCAs); related plant vulnerabilities are clogging of suction lines for the containment sump during LOCAs and the very restrictive conditions for High Pressure Injection System (HPIS) operation. Operator errors are dominant contributors because of inadequate emergency operating procedures currently in effect.

I. INTRODUCTION

Ukraine operates three kinds of pressurized water reactors of Soviet-design, VVER-440/213, VVER-1000/302 (the older, so-called "smaller" 1000 series), and VVER-1000/320, their most modern 1000 MWE nuclear power plants. There are two VVER-440/213 and one VVER-1000/320 at Rivne, two VVER-1000/302 and one VVER-1000/320 at South Ukraine, six VVER-1000/320 at Zaporizhzhya, the largest power station in Europe, and one VVER-1000/320 at Khmelnitskyy. All Ukrainian plants are currently operating with annually renewable permits until they update their safety analysis reports (SARs). After approval of the SARs by the Ukrainian Nuclear Regulatory Authority, the plants will be granted long-term operating licenses.

In September 1995, the Nuclear Regulatory Authority (NRA) of the Ministry for Environment and Nuclear Safety (MINECOBEZPEKA) and the state utility, then organized as the Government Nuclear Power Coordinating Committee of Ukraine (DERZHKOMATOM), issued a new contents requirement for the safety analysis reports of VVERs in Ukraine. It contains requirements in three major areas: design basis accident (DBA) analysis, probabilistic risk assessment (PRA), and beyond design-basis accident (BDBA) analysis. The DBA requirements is an expanded version of the older SAR requirements. The last two requirements, on PRA and BDBA, are new.

The schedule for submitting and approving the updated SARs is tight and the US Department of Energy (USDOE), through the Soviet-Designed Reactor Safety activities of the International Nuclear Safety Program (INSP), has initiated an assistance and technology transfer program to Ukraine to assist their nuclear power stations in developing a Western-type technical basis for the new SARs. The INSP is managed on behalf of DOE by the Pacific Northwest National Laboratory (PNNL) and Argonne National Laboratory (ANL) is responsible for the technical integration of all plant safety evaluations and specifically for the management and coordination of the in-depth safety assessments (ISAs).

USDOE sponsored in-depth safety assessments (ISAs) are in progress at three nuclear reactor pilot units selected by Ukraine, South Ukraine Unit 1 (VVER-1000/302), Zaporizhzhya Unit 5

(VVER-1000/320), and Rivne Unit 1 (VVER-440/213). In addition, a first follow-on ISA project for a VVER-1000/320 reactor has been initiated at Khmelnytskyy Unit 1.

The emphasis in this paper is on the programmatic aspects of the ISAs and the role of the Level 1 Internal Events PRA. Hence, the following sections briefly outline the objectives and approach of the ISAs as well as the current status of the ISA projects in Ukraine. Finally, the currently available results and inferences from the Level 1 Internal Events PRAs and from related analyses are summarized and discussed.

II. OBJECTIVES AND APPROACH OF IN-DEPTH SAFETY ASSESSMENTS (ISAs)

The objectives of the DOE-sponsored plant-specific ISAs in Ukraine are: (i) to provide the technical basis for the required Safety Analysis Reports (SARs); (ii) to develop a documented safety basis, as well as a basis for plant upgrades and for evaluating changes in plant operation; and (iii) to develop indigenous capabilities in Ukraine to perform ISAs and capabilities at the nuclear power plants (NPPs) to use up-to-date methods for controlling the plant configuration to keep it within its safety envelope. Validated non-commercial US computer programs are provided to Ukrainian organizations to carry out the analytical work. These include thermal hydraulic and accident progression analysis codes such as RELAP5, CONTAIN, and MELCOR.

The ISA work is performed by Ukrainian organizations with the NPP responsible for the overall project management. To provide maximum technical and management assistance as well as nuclear safety technology transfer to the Ukrainian project team, the DOE INSP selects and funds an experienced US nuclear safety contractor. For the three pilot projects in Ukraine the selected contractor is SCIENTECH, Inc., and for the Khmelnytskyy project the contractor is Science Applications International Corporation (SAIC).

The ISA projects encompass most areas of plant safety evaluation, including design basis accident (DBA) analysis, limited beyond design basis accident (BDBA) analysis, and an assessment of external events and internal hazards (fires and flooding). However, the initial and primary emphasis is on performing a detailed, plant specific, Level 1 Internal Events PRA. This allows the early development of the plant risk profile, the identification of risk significant accident sequences and plant vulnerabilities, and provides guidance for the remainder of the safety assessments.

In parallel to the Level 1 Internal Events PRA analysis, all the data bases necessary to support the probabilistic and deterministic safety analyses are assembled, and the required thermal hydraulic models are developed. A very important aspect of each project is the development of detailed project guidelines. These are based on international standards and serve as a guide for performing and reviewing the work. The guideline development is also an excellent process for technology transfer and training of the Ukrainian project teams. In order for the work products to be able to pass international peer review, USDOE will fund a separate Ukrainian team to conduct quality assurance and peer review of the ISA work. More detail on the ISA scope and approach is given in Reference 2.

III. STATUS OF ISA PROJECTS IN UKRAINE

a. South Ukraine Unit 1 - ISA

Among the three major ISA projects in Ukraine the most advanced study is that at South Ukraine Unit 1, the VVER 1000/302 pilot plant. The project guidelines development and the data collection and analysis effort have been completed. The latter include the detailed systems description data base, the equipment reliability data base, the nuclear steam supply system (NSSS) data base, the abnormal events data base and the containment data base. Work on the Level 1 Internal Events PRA is essentially complete. A verified and validated RELAP5 model has been developed and the success criteria calculations have been completed. Initiating events have been identified and grouped, systems analysis (fault tree analysis) has been completed as has the human reliability analysis. Accident sequence analysis (fault tree development) and the quantification calculations (using the IRRAS computer codes), to identify the risk dominant sequences and events have also been completed. Final results from the Level 1 Internal Events PRA are in hand and the dominant risk contributors have been identified. Preparation of the final report is nearing completion.

Significant progress has also been made on the design basis accident (DBA) analysis for South Ukraine Unit 1. The important initiation events and accident sequences have been identified and grouped. The RELAP5 model has been modified to accommodate the DBA analysis and models for the CONTAIN and MELCOR codes have been developed. These will be used to determine containment loads and accident progressions. Similarly an ORIGEN code model was developed for the determination of radionuclide inventories.

Work is also in progress for South Ukraine Unit 1 on the assessment of the risk/impact of internal hazards (fire and flooding) and external events, the latter including both man-made hazards and natural phenomena hazards (NPHs). The first phases of these studies, which are nearing completion, concentrate on data collection, hazard identification and screening, and the development of approaches for the final phases of the investigations.

Other aspects of the ISA, such as Level 2 PRA and/or beyond design basis accident (BDBA) analysis, are still being formulated. Completion of the entire ISA for South Ukraine Unit 1 is projected for late in the year 2000.

b. Zaporizhzhya Unit 5 - ISA

The ISA at Zaporizhzhya Unit 5 (ZNPP5) is the pilot project for all the VVER-1000/320 units. This is the most common reactor type in Ukraine (9 units). Again, the initial effort concentrates on completing the Level 1 Internal Events PRA. A set of project guidelines for the Level 1 PRA has been developed, as have been drafts for the remaining project guidelines. Work is in progress on developing plant specific data bases and the RELAP5 model for the nuclear steam supply system (NSSS). Among the data bases the NSSS data base is complete as are the systems descriptions. Preliminary versions of the component reliability data base and the abnormal events data base have been completed. Much progress has also been made towards completing the systems analysis (fault trees). Completion of the Level 1 Internal Events PRA is projected for the end of 1999 and completion of the entire ISA effort is expected in mid 2001.

c. Rivne Unit 1 - ISA

At Rivne Unit 1, the pilot plant for VVER/440-213 units, a significant portion of a Level 1 Internal Events PRA was completed prior to the initiation of the DOE supported ISA project. However, this work was more in the nature of a training effort or demonstration project. It lacked stringent quality assurance (QA) procedures and relied heavily on generic data. The completion of this PRA is one of the first priorities of this project. A detailed evaluation of the prior analysis has resulted in the development of the most efficient approach for completing the PRA. To establish more plant specific data bases, data collection is in progress. The preparation of project guidelines has essentially been completed. Other aspects of the ISA such as the DBA analysis have also been started. Again, completion of the project is projected for late 2000.

d. Khmelnytskyy Unit 1 - ISA

As indicated earlier the ISA for Khmelnytskyy Unit 1 is the first follow-on study for a VVER-1000/320 Unit. It will utilize the results from the Zaporizhzhya Unit 5 study for its safety assessment. This is the most recently initiated ISA in Ukraine and work is initially concentrating on plant specific data collection. These data bases will be compared in detail with those from the Zaporizhzhya Unit 5 ISA to establish any significant differences between the units. This will then define the modifications in the analysis that are necessary to establish the risk profile for the Khmelnytskyy Unit. Effort is also in progress to develop an efficient methodology to implement such a difference analysis. Completion of this ISA is not projected before the end of 2001.

IV. PRA RESULTS

A. Summary of Results for South Ukraine Unit 1 (VVER-1000/302)

To date the only completed Level 1 Internal Events PRA is that for South Ukraine Nuclear Power Plant (SUNPP) Unit 1. The results have undergone thorough internal reviews. However, they have not been subjected to an independent external peer review. Thus, the estimates of core damage frequency are tentative values. However, they appear to be reasonable in light of the International

Atomic Energy Agency (IAEA) recommended value for existing nuclear power plants.[3] As may be expected, the estimates are considerably higher than the target IAEA and OPB-88[4] values for the new projects.

Loss of coolant accidents (LOCAs) are the dominant initiating events contributing to risk at SUNPP Unit 1. The frequency of core damage resulting from LOCAs represent 53.9% of total core damage frequency. Very small LOCAs are the most dominant of all initiating events, responsible for 35.4% of the total core damage frequency. Very small LOCAs are so dominant because their frequency is quite high (one in every four years).

The next most dominant initiating event is also a LOCA (a large LOCA), which contributes 13.1% of the total core damage frequency. Clogging of suction lines from the containment sump is a dominant failure mechanism for this initiator. Sump filter clogging is recognized as a generic safety issue for VVERs, and results from thermal insulation being dispersed into the containment by energetic depressurization events.

Transients are initiating events associated with perturbations to normal unit operations (without loss of coolant) that require a reactor trip (either automatically, or by operator action). This initiating event category includes feedwater flow upsets, turbine/condenser disturbances, anomalies in the reactor control system and safeguards functioning, as well as primary coolant flow violations. In the SUNPP Unit 1 PRA, four groups of transients, involving 27 initiating events, are analyzed and quantified. The core damage frequency due to transient initiating events is 27.3% of the total.

Transient initiating events occur relatively often at SUNPP Unit 1. As a rule, such events are routine and familiar to plant operating personnel. Moreover, success criteria for transient initiators are less stringent (i.e., more forgiving) than for other initiating event categories. Therefore, transient initiating events (the most likely to occur) have a lesser impact on the core damage frequency because the probability of successfully preventing core damage, given a transient initiator, is quite large. The most risk significant transient initiator is loss of offsite power, which is 10.2% of the total core damage frequency.

Special initiating events result in the dependent failure or degraded operation of at least one system needed for safe shutdown. This initiating event category includes support system failures, steam generator tube leaks and manifold ruptures, steam and feedwater pipe ruptures inside and outside the containment, plus primary coolant leaks outside containment. Such events engender conditions for direct radioactivity release to the environment that could be followed by an unisolatable LOCA that impacts the long-term heat removal safety function. The core damage frequency attributable to special initiators represent 18.7% of the total.

Special initiating events have a high conditional core damage probability. This is because special initiating events are: (i) characterized by significant impact on safety system and safety significant system availability; (ii) plant-specific (which leads to difficulty in modeling the unit response, resulting in the application of conservative assumptions and end state estimate); as well as (iii) characterized by demands on non-standard (rarely applied) human actions.

This last consideration produces short response time limits and extremely high stress levels, leading to a high probability of operator error. Medium primary to secondary side LOCAs are the most risk dominant special initiating events, constituting 10.6% of the total core damage frequency.

The PRA results indicate that anticipated transients without scram are a negligible risk contributor because reactivity control can readily be achieved by boron injection if the control rods fail to produce a subcritical state.

Operator errors are dominant contributors to risk at SUNPP Unit 1. The salient reason for this conclusion is that emergency procedures presently in effect are event-oriented. Developing and implementing symptom-based procedures should dramatically improve safety. A second reason is that there is no full-scale simulator for SUNPP Unit 1 (although one is being developed). Hence, instead of relying on empirical simulator data, the human reliability analysis was largely performed using theoretical models predicated upon project guidelines and thermal hydraulic calculations. Due to the complex interrelationship between the plant environment and operators during certain accident conditions, conservative assumptions were adopted to simplify the analysis. Such assumptions result in overestimation of human error probabilities.

Two design related problems of significance relative to risk at SUNPP Unit 1 and similar reactors are: (1) use of heat insulation that can be dispersed during energetic primary circuit depressurization events, thereby clogging the containment sump filters; and (2) very restrictive conditions for High Pressure Injection System (HPIS) operation.

The HPIS design restrictions are the inability to: (i) use it under low pressure conditions (below 40 bar); and (ii) operate HPIS in a recirculation mode (because its suction has no connection to the containment sump). These design problems severely limit the condition under which HPIS can be used to prevent core damage, and exacerbate demands on the low pressure injection system.

B. Results for Zaporizhzhya Unit 5 (VVER-1000/320)

No estimates of core damage frequency or of the major contributors to risk are yet available for Zaporizhzhya Nuclear Power Plant (ZNPP) Unit 5. However, the preliminary analysis of the data being collected in support of the PRA effort indicate some interesting trends. An example of this is the treatment of abnormal events. The data base indicates one hundred and two events were identified in the seven year period analyzed. Of this number 26 need to be considered for inclusion in the list of plant specific initiating events.

These events fall into four broad categories. In the first category "immediate reactor scram" there have been five events over the seven years yielding a frequency of approximately .9/reactor year (RY). In fact there has only been one such event in the past four years, and non in the last year, so the frequency appears to be decreasing as operating experience grows. In the second category "reactor scram after a short delay" there have been two events in the seven years. These events occurred in 1994 and 1995. If it is considered that the time to scram was short enough for the events to be combined with those in the first category, the combined frequency is approximately 1.2/RY. Again if the first two categories are combined there has only been 1 event in the past two years, indicating a downward trend.

There have been 11 manual shutdowns for planned and unplanned maintenance over the seven year period. This may have some impact in the PRA if it is found that the shutdown was the result of the unavailability of safety systems used during the shutting down process, and would therefore need to be considered in the future.

There have been 8 turbine trips in the period under investigation, which, taking into account the time the turbine was online is equivalent to approximately 1.5/RY. Because of the impact of the Fast Power Reduction system and Turbine Bypass Capacity these did not result in scram, as would have been the case in most Western PWR designs. However, it is also significant to note that there have been no turbine trips recorded since 1993. The reason for this is that the earlier analogue turbine control system was replaced with a new digital system.

The information provided in the database identifies the initiating events which have occurred at ZNPP Unit 5 over the past seven years, the root cause of the event, and any consequential or coincidental component/system failures that have occurred. This information will be used in the development of the event trees and the reliability data assessment for the systems in question.

The response of the operator to a number of the events can also be used as one of the inputs when assessing the reliability data for operator response to the failure of systems or following a given initiating event. The grouping of the individual events into the initiators for which event trees will be developed will be based on the safety functions required to maintain decay heat removal following the occurrence of the event.

C. Results for Rivne Unit 1 (VVER-440/213)

As indicated earlier a partial Level 1 PRA of internal initiators was completed prior to the current ISA for Rivne Nuclear Power Plant (RNPP) Unit 1. However, this earlier effort was intended as a demonstration project and training effort, and should not be considered as a true PRA analysis of the Unit. The work does not meet all of the quality assurance (QA) requirements of a Western-style PRA, and relied heavily on generic data. Results from this study were reported in detail in an earlier paper.[5] A unique attribute of this work is that the risk assessment was performed using the REVEAL_W™ software package,[6] which uses the master plant logic diagram (MPLD) concept and works in success space, rather than failure space, as is common for other risk quantification software.

To take best advantage of the existing results the effort under the current ISA will continue using this approach.

The numerical values of core damage frequency from the demonstration study appear optimistic and should be treated with much caution. However, the relative contribution of various initiating events again indicate that loss of coolant accidents (LOCAs) dominate, with medium LOCAs contributing more than 50% to core damage frequency. Other major contributors are loss of offsite power (18.2%) and primary to secondary leaks, such as steam generator manifold rupture (12.9%) and steam generator tube rupture (13.7%). These results will need to be confirmed as part of the current study.

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- South Ukraine Nuclear Power Plant (SUNPP) Unit 1 - ISA

The major technical work is performed by Energorisk, Ltd., Kyiv with contributions from the SUNPP Technical Staff. The U.S. technical assistance contractor is Scientech, Inc. Key personnel are:

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- Zaporizhzhya Nuclear Power Plant (ZNPP) Unit 5 - ISA

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- Rivne Nuclear Power Plant (RNPP) Unit 1 - ISA

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- Khmelnytskyy Nuclear Power Plant (KhNPP) Unit 1 - ISA

The technical work is being performed by Energoprojekt - Kyiv (KiEP) jointly with the plant technical staff. The U.S. technical assistance contractor is Science Applications International Corporation (SAIC). Key personnel are:

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