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Full-Scope Probabilistic Safety Assessment of Balakovo Unit 1 in Russia

The Balakovo Nuclear Power Plant operating in Russia has four operating units of a VVER-1000 type. The first unit was connected to the grid on Dec. 28, 1985, and put in commercial operation on May 23, 1986. According to modern requirements of the Russian Nuclear Regulatory Authority, the full-scope probabilistic safety assessment (PSA) must be performed to extend the license for operation beyond an initial 30-year lifetime of the unit. The paper presents the results of the Level 1 PSA covering internal initiating events for power and shutdown operational plant states, internal hazards (fires and floods), and external hazards, including natural and man-made events, in particular, seismic impact, and aircraft crash. [DOI: 10.1115/1.4033087]

Introduction

The Balakovo Nuclear Power Plant operating in Russia has four operating units of a VVER-1000/320 type. The first unit was connected to the grid on Dec. 28, 1985, and put in commercial operation on May 23, 1986. This is the first unit of this type constructed in Russia followed by construction of nine additional units in the country. The four-loop unit of VVER-1000/320 involves primary-circuit hydroaccumulators inside the containment and active safety systems having physically and functionally separated three trains. For instance, diesel-generator buildings are located on the opposite sides of the containment.

Other plants of this generation operate in Ukraine, Bulgaria, and the Czech Republic. According to modern requirements of the Russian Nuclear Regulatory Authority, Rostechnadzor, the full-scope PSA must be performed to extend the license for operation beyond an initial 30-year lifetime of the unit [1,2].

The paper discusses the methodology, scope, and results of the Level 1 PSA covering internal initiating events for power and shutdown operational plant states, internal hazards (fires and floods), and external hazards, including seismic PSA.

The Russian Rules [2,3] and IAEA Guide [4] recommend that PSA Level 1 should take into account the potential triggering events for all radioactive sources, particularly in the spent fuel pool, not only in the core. The paper addresses both radioactive sources.

PSA for Internal Initiating Events

The methodology of PSA Level 1 for internal initiating events is based on the small-event trees/large-fault trees method, which is recommended by international and Russian guides [3,4]. The scope of the analysis includes all necessary tasks such as definition of operational states, selection and grouping of initiating events, accident sequence modeling supported by thermohydraulic calculations using the best-estimate code KORSAR/B1.1 [5], system, data and human reliability analyses, development of the unit integral model using the RiskSpectrum code [6], and quantification, including uncertainty, sensitivity, and importance analyses as well as interpretation of results.

Reliability database is mainly created from operating experience of the Balakovo NPP. The source of data for estimating the frequency of frequent initiating events was the operating experience of Russian VVER-1000 plants. Frequencies of rare initiating events were estimated using analytic methods, e.g., fracture mechanics study for medium and large LOCAs and catastrophic reactor pressure-vessel rupture.

Results of PSA Level 1 for Internal Initiating Events At-Power. The mean value for the fuel-damage frequency at-power for internal initiators is estimated to be 2.17×10^{-5} per reactor year. The core-damage frequency at-power is dominant compared with frequency of heavy damage to the fuel elements in the spent fuel pool. The main contributors to the fuel-damage frequency are shown in Fig. 1.

A high importance of small secondary leaks is caused by both relatively high frequency of the initiating event and the potential dependent failures of atmospheric steam dump valves due to harsh environment conditions (high temperature and humidity). It was recommended to separate these valves and replace them with ones qualified for operation in harsh environment conditions, because the severity of such a scenario without PSA results was not understood properly in the 1980s when issuing a license. An important contributor is the compensated LOCA when the normal make-up capacity is sufficient to compensate a leak. As a result, the accident can last relatively long till an accident signal generation.

Human reliability analysis involves preaccident human errors study by the THERP method [7] and postaccident ones using the decision-tree methodology [8,9]. Initiating events caused by human errors at-power are estimated statistically. The treatment of dependent errors is of particular importance for the reserved trains of the system, which definitely implies to emergency personnel errors. The method proposed in Ref. [7] was used to evaluate dependent human error probabilities. Human dependencies are estimated using the postprocessing option for several human errors found in the same accident sequence. The fractional contribution of human errors (the fraction of minimal cut sets that involves human errors) to the fuel-damage frequency is 78%. The contribution of postaccident errors is almost completely specified in this value. Such a high importance is caused by human actions required for long-term heat removal from the reactor facility as well as managing beyond design-basis accidents such as the "feed-and-bleed" mode and connection of a movable pump unit. Some automatic algorithms to be implemented were proposed afterward, e.g., for primary-to-secondary leaks.

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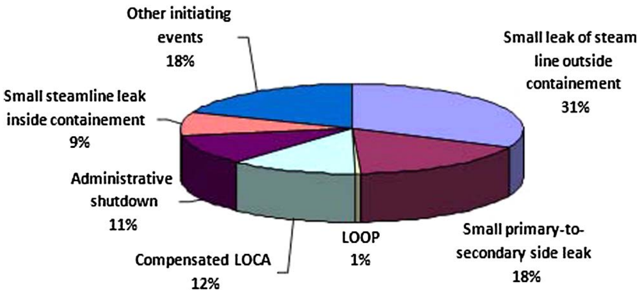

Fig. 1 Contribution of initiating event to fuel-damage frequency at-power

Results of PSA Level 1 for Internal Initiating Events in Shutdown Plant Operational States. The shutdown PSA considered three types of unit shutdown, namely, for a partial refueling, for a full refueling, and unscheduled cases for repair. The mean value of the fuel-damage frequency for all types of the unit shutdowns is 1.72×10^{-5} per year. The main contributor to this value is shutdown with the partial refueling (68% for an 18-month interval between shutdowns for refueling). The dominant initiating event is a loss of the off-site power that contributes 26.7% during such a type of shutdown. Among plant operational states, the dominant contributor is the mid-loop operation with one safety-system train taken out of service for planned maintenance when the main coolant inventory is reduced so that the level is at mid-loop elevation. It should also be mentioned that a relatively high importance of human errors potentially causing an initiating event is calculated to be about 30%. Therefore, the development of some shutdown-oriented accident procedures is recommended.

PSA for Internal Hazards

Fires and floods were considered as internal hazards according to the methodology presented in [10]. Input data collection included walkdown of the unit documented in the PSA.

Fire PSA. Main tasks of the fire PSA were the following: the definition of fire zones, selection of fire-induced initiating events, and definition of equipment damaged by a fire, fire-frequency estimation, human-reliability analysis in case of a fire, fire propagation and suppression analysis, fire-scenarios development, and quantification of the fuel-damage frequency. All these tasks were documented in the fire PSA documentation, including walkdown findings.

Thermophysical modeling of fire dynamics was performed using the CFAST code (Consolidated Fire Growth and Smoke Transport Model) [11] developed by the U.S. National Institute Standards and Technology.

Electrical components such as cables, motor, oil, hydrogen, and transient combustibles were considered as fire-ignition sources and fire loads.

The fire-induced fuel-damage frequency is quantified to be 4.24×10^{-6} 1/year. The main contribution (about 90%) is given by a fire in 13 fire zones where many important components may be damaged by a fire. On the other hand, fire propagation was found to be unimportant from the fuel-damage frequency point of view.

The dominant contributor to the fire-induced fuel-damage frequency is a fire in cable semifloors of the safety-system train. This scenario is associated with the long-term opening of an atmospheric steam dump valve. The severity of the scenario is caused by the lack of an automatic fire-suppression system, the total loss of important safety-related components in the fire zone, high human error probabilities, and the failure to isolate the stuck-open steam dump valve. According to the fire PSA findings, it is recommended to implement nonwater fire-suppression system in this fire zone and develop procedures related to manual fire suppression.

The second important contributor to the fuel-damage frequency is a fire in the turbine hall. It is caused by a relatively high frequency of the initiating event, large amount of combustibles (oil and hydrogen), and the potential for roof collapse.

The other important contributors are fires in switchgear rooms 6/0.4 and 0.4 kV, and DC rooms.

Uncertainties of the fire PSA are mainly associated with a relatively close location of the cable routes of different safety trains inside the containment. Therefore, it is recommended to install additional barriers or use special fire-resistant ducts.

Flood PSA. The main tasks of the flood PSA were the definition of flood zones; selection of flood-induced initiating events; definition of equipment damaged by a flood, flood-frequency estimation; human-reliability analysis given a flood, flood propagation, flood-scenarios development, and quantification of the fuel-damage frequency.

In performing a flood PSA, the following buildings were considered: reactor building, turbine hall, diesel-generator buildings (essential service water pumps are located inside), buildings of electrotechnical components, and unit pump station. Among flood sources were considered pipes, tanks, heat exchangers, water-fire suppression systems, valves separating water and a room, and flood-dangerous repair activity.

The total flood-induced fuel-damage frequency is estimated to be 4.22×10^{-6} 1/year. The main contribution (about 90%) is given by floods associated with 20 scenarios in which many important components may be damaged by a flood in the flood zone where flood is initiated or due to propagation from other zones. The dominant contributors to the fuel-damage frequency (about 60%) are three zones including a motor control center (leading to a transient with a loss of a number of safety-related equipment of 0.4 kV), control unit of the emergency feedwater system, and motor-operated valves of the emergency fuel cooling and primary make-up systems. The recommendation was given to improve leak resistance of the barriers in these zones to direct water to the basement and use movable pumps.

PSA for External Hazards

The PSA for external events considers natural and man-made events. Special attention was paid to seismic PSA; in particular, a comprehensive walkdown of Unit 1 was carried out for the first time in the history of Russian VVER-1000 plants.

Seismic PSA. Buildings that collapse during the earthquake and can cause the initiating events were selected for the seismic PSA. They include the reactor building, diesel-generator buildings, spray ponds, the turbine hall, switchyards, transformers, and other electric components located outside the buildings.

The seismic PSA includes the following tasks [12,13]: the development of a seismic hazard curve, selection of components for analyses, determination of component seismic margin based on results of unit walkdown, preliminary and final component and structures fragility analysis using calculation of seismic margins, estimation of seismic-induced frequencies of initiating events, human-reliability analysis during a seismic event, development of seismic event trees, and the integral seismic PSA model, quantification of the fuel-damage frequency for different seismic impacts and the total one.

The mean seismic hazard curve (mean value) for the Balakovo site as a result of probabilistic seismic hazard analysis developed within one of the steps of current seismic PSA is shown in Fig. 2.

The results of conditional core-damage frequency calculation for different seismic PGA events are shown in Table 1. The main contributions are seismic events having peak ground acceleration as a fraction of gravity acceleration of 0.18 and 0.24 $g\,m/s^2$, i.e., events having annual frequency between 1.0×10^{-5} and 1.0×10^{-6} 1/year. The total estimate of the mean value of mean fuel-damage frequency

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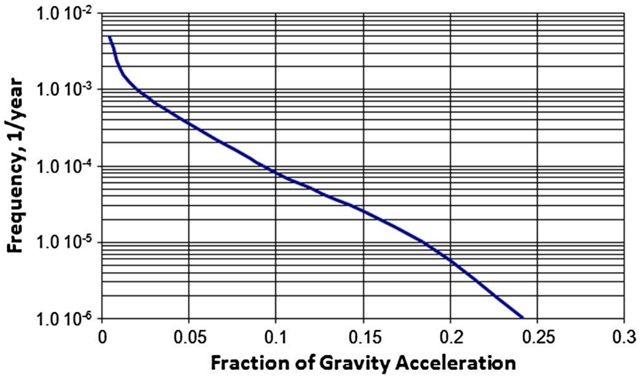

Fig. 2 Seismic hazard curve for the Balakovo site

Table 1 Results of the seismic-induced fuel-damage frequency calculation

PGA as a fraction of gravity acceleration g (m/s^2)	Conditional probability of the fuel damage
0.093	3.81×10^{-3}
0.12	7.38×10^{-3}
0.18	1.44×10^{-1}
0.24	8.61×10^{-1}

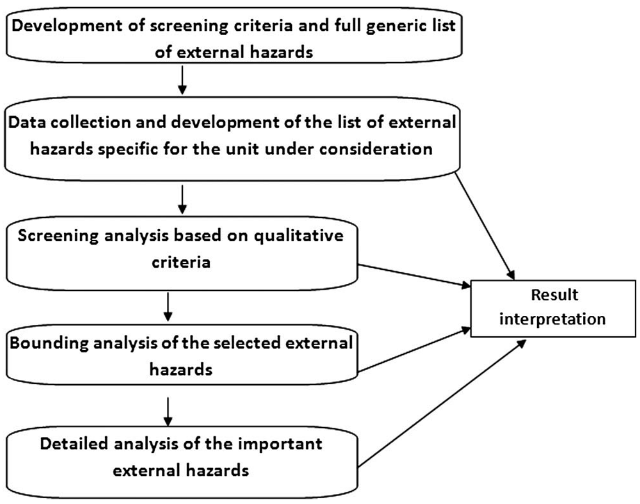

Fig. 3 Stages of the external hazard PSA

obtained by convolution of mean fuel-damage fragility with seismic hazard curve is estimated to be 3.09×10^{-6} 1/year.

The main contribution to the fuel-damage frequency gives failures of cable trays and a damage of the turbine hall. It is strongly recommended to make modernization to some of the cable-framework constructions. As a result of the walkdown and seismic PSA, more than 250 recommendations were generated to enhance safety of the Balakovo Unit 1.

Other External Events. The methodology used for the analysis of other external events is recommended by the Russian Regulatory Rules [14]. The approach that is applied is shown in Fig. 3.

External hazards, such as meteoritic fall, aircraft crash, and explosions potentially leading to the fuel damage but having a frequency less than 1.0×10^{-6} 1/year, were screened out from the consideration. In particular, the potential for aircraft crashes that may affect the plant site was considered. A crash that may occur at the site was derived from the general air traffic in the region. The probability of an aircraft crashing in the region was determined for each class of aircraft considered (small, medium, and large civil and military aircraft with weight more than 60 tons). The total frequency of an aircraft crash event was estimated to be 9.35×10^{-8} 1/year.

Table 2 Fuel-damage frequency caused by the external hazards (except for seismic events)

External hazard	Fuel-damage frequency, 1/year	Comments
Site flooding caused by a dam failure of the Saratov artificial lake (human-induced accident)	1.0×10^{-6}	Bounding estimation
Tornado impact at spray ponds plus the loss of off-site power	3.52×10^{-6}	Bounding estimation
Combination of weather conditions (snow, wind, ground surface icing)	1.93×10^{-7}	Detailed analysis
Tornado impact at the turbine building	1.02×10^{-10}	Detailed analysis
Extreme wind	1.02×10^{-9}	Detailed analysis
Extreme snowfall	1.63×10^{-7}	Detailed analysis
Total, all the external hazards except for seismic events	4.88×10^{-6}	

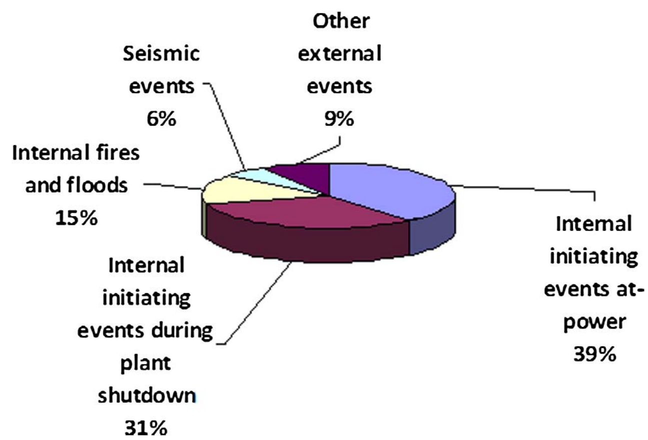

Fig. 4 Contribution to the fuel-damage frequency from different categories of initiators

A bounding analysis was performed for the following external hazards: external flooding, strong wind, icing, and snow loads. For some of them, a detailed analysis was conducted using a probabilistic model. The results of the analysis of the external hazards except for the seismic impact are shown in Table 2.

The dominant contributor to the fuel-damage frequency is the event associated with damage to the service water-spray ponds by a tornado. It should be noted that quite conservative assumptions were accepted that all the ponds would be damaged. However, it was found that the existing database is obsolete and needs to be updated. In addition, post-Fukushima equipment not considered to cope with this beyond design-basis accident may be used. Therefore, this result is believed to be conservative.

Conclusion

The total fuel-damage frequency is calculated to be 5.52×10^{-5} 1/year. Figure 4 shows that the dominant contributor to the fuel-damage frequency is internal initiating events.

A relatively low importance of internal hazards is supported by good physical and functional separation of safety-system trains. The only exception is potential steaming of the secondary-side

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steam-relief valves taken into account the internal event PSA at-power. A low seismicity of the site led to low contribution from seismic events.

The full-scope PSA Level 1 was carried out for the first time in Russia. Its results are applied for an extension operating license.

Safety level of the Balakovo Unit 1 estimated by the full-scope Level 1 PSA is acceptable, because it is approximately 50% lower than the fuel-damage frequency value of 1.0×10^{-4} events per plant-operating year given in INSAG-12 [15] as the target for existing nuclear power plants. Nevertheless, recommendations developed using PSA findings are going to be implemented to enhance safety of the Balakovo Unit 1.

Acknowledgment

The PSA has been carried out by the Atomenergoproekt, Moscow. Balakovo plant personnel were also extensively involved in the PSA development.

Nomenclature

DC = direct current
g = gravity acceleration, $\mathrm{m/s^2}$
IAEA = International Atomic Energy Agency
LOCA = loss-of-coolant accident
PGA = peak ground acceleration, $\mathrm{m/s^2}$
PSA = probabilistic safety assessment
THERP = technique for human error-rate prediction

References

[1] Rostechnadzor of the Russian Federation, 2008, "Administrative Regulations for Execution of State Function of Licensing Activities in the Area of Utilization of Nuclear Power by Federal Service for Environmental, Technological and Nuclear Regulation," Rostechnadzor of the Russian Federation, Moscow.

[2] Rostechnadzor of the Russian Federation, 2015, "General Provisions of Safety of Nuclear Power Plants," Rostechnadzor of the Russian Federation, Moscow, NP-001.

[3] Rostechnadzor of the Russian Federation, 2011, "Provisions of Main Recommendations on Conducting Level 1 Probabilistic Safety Assessment for Internal Initiating Events occurring at All Plant Operational Modes," Rostechnadzor of the Russian Federation, Moscow, RB-024-11.

[4] International Atomic Energy Agency, 2010, "Development and Application of Level 1 Probabilistic Safety Assessment for Nuclear Power Plants," *IAEA Safety Standards, Specific Safety Guide SSG-3*, IAEA, Vienna.

[5] Migrov, Ju. A., *The First Base Version Thermohydraulic Code KORSAR/B1.1*, FGUP NITI, Russia, 2002.

[6] Risk Spectrum, Lloyd's Register Consulting, Version 3.1.0, http://www.riskspectrum.com/en/risk/

[7] Swain, A. D., and Guttman, H. E., 1983, *Handbook of Human Reliability Analysis With Emphasis on Nuclear Power Plant Applications (THERP)*, NUREG/CR-1278, Sandia National Labs, Albuquerque, NM.

[8] Spurgin, A. J., Moieni, P., Gaddy, C. D., Parry, G., Orvis, D. D., Spurgin, J. P., Joksimovitch, V., Gaver, D. P., Hannaman, G. W., 1990, "Operator Reliability Experiments Using Power Plant Simulators," Electric Power Research Institute, Palo Alto, CA, EPRI NP-6037.

[9] Bareith, A., and Spurgin, A. J., 1997, "Treatment of Human Factors for Improvements at the Paks Nuclear Power Plant," PSAM-III International Conference on Probabilistic Safety Assessment and Management, Crete, Greece, Springer London Ltd, Godalming, Surrey.

[10] Rostechnadzor of the Russian Federation, 2012, "Provisions of Main Recommendations on Conducting Level 1 Probabilistic Safety Assessment of Nuclear Power Plant for Initiating Events Caused by Internal Fires and Floods," Rostechnadzor of the Russian Federation, Moscow, RB-076-12.

[11] CFAST—Consolidated Model of Fire Growth and Smoke Transport (Version 6.2), 2013, Technical Reference Guide, National Institute of Standards and Technology, fire.nist.gov/bfrlpubs/fire04/PDF/f04046.pdf.

[12] 1002989, 2003, *Seismic Probabilistic Risk Assessment Implementation Guide*, EPRI, Paolo Alto, CA.

[13] IAEA-TECDOC-724, 1993, *Probabilistic Safety Assessment for Seismic Events*, International Atomic Energy Agency, Vienna, Austria.

[14] Gosatomnadzor of the Russian Federation, 2014, "Recommendations on Performing Level 1 Probabilistic Safety Assessment of Nuclear Power Plant for Initiating Events of External Natural and Man-made Origin," Rostechnadzor of the Russian Federation, Moscow, RB-021-14.

[15] International Atomic Energy Agency, 1999, "Basic Safety Principles for Nuclear Power Plants: 75-INSAG-3 Rev. 1: A Report by the International Nuclear Safety Advisory Group," International Atomic Energy Agency, Vienna, INSAG-12.

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