Risk-informed prioritization of modernization activities using ageing PSA model

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Abstract: Nuclear Power Plant modernization is a continuous process, which is aimed to reduce risk as low as reasonably achievable. Modernization process is especially important for old design NPPs to keep them in compliance with current safety standards. In addition, modernization process is important for plants where ageing is becoming more and more significant factor in regard with equipment reliability. Development of modernization program requires not only listing the issues to be addressed, but also to come up with common understanding of importance of proposed measures and their priority. Traditionally prioritization of modernizations is mainly done using deterministic considerations. Meanwhile parallel application of PSA models allow to come up with numerically justified and optimal solutions. Incorporation of ageing aspects in PSA model provide additional information for modernization prioritization in regard with plant's components ageing perspective. This paper describes a feasibility study aimed to use integrated risk-informed decision-making principles for prioritization of modernizations. Paper discusses proposed approach for prioritization, which implies combination of probabilistic and deterministic indicators. In addition, paper discusses comparative analysis of results obtained using base case PSA model and ageing PSA model.

Keywords: Ageing PSA, time-dependent reliability, risk-informed decision making, modernization

1. INTRODUCTION

Modernization process is integral part of Nuclear Power Plant operation, which is mainly aimed on plant safety improvement. Continuous risk reduction through modernization activities is an essential part of ALARA principle. Modernization process is especially important for old design NPPs which were designed without taking into account current safety standards. In addition, one of the problem of old design NPPs is ageing factor, which is becoming more and more significant factor in regard with equipment reliability.

Plant modernization program is usually based on results of safety assessment, operational experience analysis and best international practice. All of the mentioned aspects assist to reveal plant weaknesses and construct comprehensive list of measures to be implemented for safety enhancement. However development of modernization program requires not only listing the issues to be addressed, but also to their categorization and setting up implementation priority.

Prioritization of modernizations is done using combination of deterministic and probabilistic considerations. Incorporation of ageing aspects in PSA model provide additional information for modernization prioritization in regard with plant's components ageing perspective.

This paper describes a feasibility study aimed to use integrated risk-informed decision-making principles for prioritization of modernizations. Calculations have been performed using plant-specific PSA models developed for Armenian NPP Unit 2. Feasibility study was performed in the frame of Ageing PSA European Network organized by Institute for Energy and Transport (EC JRC, Petten).

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2. DESCRIPTION OF PSA MODELS AND OBTAINED RESULTS

Base case and ageing PSA models of Armenian NPP Unit 2 have been used as a base for prioritization of plant modernizations. The scope of mentioned models is following:

- Undesired event considered: Damage of the fuel located in the reactor core
- Considered regimes: 50-100% of nominal power (regimes with both turbines in operation)
- Considered initiators: Internal initiating events

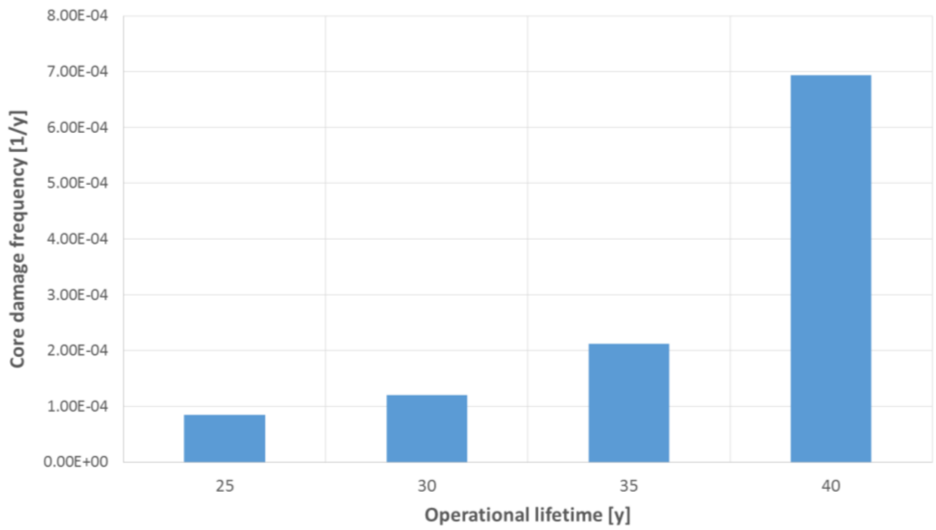
Armenian NPP Unit 2 Ageing PSA model was developed using results of time-dependent reliability analysis for selected equipment [1]. Failure records have been thoroughly examined in order to identify increasing ageing trend or to assure applicability of constant failure rate model for selected equipment. Data for time-dependent reliability analysis have been gathered from several sources: plant-specific information, data from other VVER-440 reactors [2] and generic sources [3]. Time-dependent reliability analysis was performed using best-fit model criteria [4]. Results of time-dependent reliability analysis shows increasing ageing trend model for several components modeled in current PSA, it was also proved that for the rest of component constant failure rate model is applicable [5]. Identified patterns of ageing trends have been integrated in existing PSA model and ageing PSA model was created. Base case PSA model corresponds to 25 year of plant operation. 30, 35, and 40 year's prediction has been made for selected components using information about components' reliability behavior in time. Consequently, all PSA model calculations have been made for 4 lifetime points: 25, 30, 35 and 40 respectively.

Ageing PSA model quantification was implemented for all selected lifetime periods. Integrated APSA model has been recalculated for each considered case (30 years, 35 years, 40 years and 45 years) using following assumptions:

- No any modernizations or significant replacement of equipment is foreseen
- CCF models recalculated based on new reliability parameters' values (see tables 2 and 3)
- Human error probabilities are constant
- Maintenance unavailability values are correlated with increasing failure rates.
- Error factors assigned to reliability parameters are not dependent from failure rate values

Core damage frequency analysis results for base case and ageing PSA models presented in Figure 1.

Figure 1: Results of CDF calculations for base case and Ageing PSA model



Detailed investigation of received minimal cutsets shows that risk profile is changing in time. It was noticed that though main contributors (primary and secondary side breaks) do not change significantly in time, the overall proportion of their contribution is decreased meanwhile the role of transients increased. In addition, importance analysis performed for component level reveals significant changes of risk importance parameters (e.g. Fussel-Vessely parameter) in time [6].

3. RISK-INFORMED PRIORITIZATION OF MODERNIZATION ACTIVITIES

3.1. Planned Modernization Activities

Analysis was performed for modernization activities planned for Armenian NPP Unit 2. Armenian Nuclear Power Plant (ANPP) is VVER-440/270 type reactor installation, which was designed in 70's using USSR standards. Unit 2 was commissioned in 1980 and permanently shut down for the period from 1989 to 1995. Modernizations were continuously implemented during ANPP operational lifetime (including pre start-up period from 1991 to 1995).

Currently ANPP modernization program implies implementation of several measures identified by different basis: results of safety assessment, operational experience analysis and best international practice. Major items of the program that have been selected for detailed analysis are listed below:

- Complex investigation of reactor pressure vessel resource
- Modification of the spray system Modernization against sump clogging effect (installation of effective grid system)
- Evaluation of essential service water system's pipeline breaks in boron room (flooding and spray effect analysis)
- Modernization of ECCS (reliability enhancement measures)
- Confinement safety valves reliability enhancement
- Improvement of confinement leak-tightness
- Installation of remote shutdown panel
- Verification of the capability of ventilation system to provide adequate cooling of safety system compartment after reconstruction of ECCS and spray system.
- Verification of the capability of ventilation system for cooling of reliable power supply switchgear
- Reliability enhancement of residual heat removal (RHR) system
- Complex evaluation of PTS phenomena
- Modification of emergency feedwater system (reliability enhancement measures)
- Modification of the primary circuit overpressure protection system
- Secondary side piping reliability assessment
- Investigation of external grid recovery action in case of LOSP
- Enhancement of reactor protection system reliability

3.2. Modernizations Prioritization Approach

The proposed approach for modernizations prioritization implies consideration both deterministic and probabilistic outputs for each measure listed in subchapter 3.1.

In terms of safety-related measures prioritization the main qualitative (deterministic) reference is list of safety issues specific for VVER-440 type reactors. Categorization and descriptions of VVER-440 safety issues are presented in IAEA TECDOC-640 [7]. Issues both related to design and operation are ranked according to their safety significance in four categories of increasing severity.

- Category I: Issues in Category I reflect a departure from recognized international practices. It may be appropriate to address them as part of actions to resolve higher priority issues.
- Category II: Issues in Category II are of safety concern. Defense in depth is degraded. Action is required to resolve the issue.
- Category III: Issues in Category III are of high safety concern. Defense in depth is insufficient. Immediate corrective action is necessary. Interim measures might also be necessary.

- Category IV: Issues in Category IV are of the critical concern. Defence in depth is unacceptable. Immediate action is required to overcome the issue. Compensatory measures have to be established until the safety problems are resolved.

In its turn PSA output implies information on dominant initiating events (IE) contribution and risk importance parameters for systems.

First PSA output (dominant IEs) could be interpreted as a contribution to core damage frequency from different IE categories. From this point of view following four contribution groups have been considered:
- 1st group (high importance): CDF_{IE} (contribution from particular IE category) > 30% of overall CDF
- 2nd group (medium importance): 30% of total CDF > CDF_{IE} > 20% of total CDF
- 3rd group (low importance): 20% of total CDF > CDF_{IE} > 10% of total CDF
- 4th group (negligible): CDF_{IE} < 10% of total CDF

Second PSA output (system risk importance) and its grouping was done based on Fussel-Vessely (FV) parameter which was used as an indicator for system importance. Systems have been grouped based on FV value. From this point of view following four risk importance groups are considered:
- 1st group (high importance): FV > 1E-01
- 2nd group (medium importance): 1E-01 > FV >1E-02
- 3rd group (low importance): 1E-02 > FV > 1E-03
- 4th group (negligible): FV < 1E-03

Final priority of specific planned modernization activity was made by combining IAEA-TECDOC-640 categorization [7] with the PSA outputs in terms of IE contribution and risk importance grouping presented above. Combination of mentioned factors made using risk-informed matrix presented in Figure 2.

Figure 2: Risk-infromed prioritization matrix

		PSA output			
		1st group (high)	**2nd group (medium)**	**3rd group (low)**	**4th group (negligible)**
TECDOC-640	**Category IV**	I	II (a)	III (a)	III (b)
	Category III	II (a)	II (b)	III (b)	IV
	Categories I & II	III (a)	III (b)	IV	IV

3.3. Modernizations Prioritization Results

Modernizations prioritization was done using matrix presented in Figure 2 by applying base case PSA and ageing PSA models. Base case PSA model reflects current state of equipment reliability, whereas ageing PSA model takes into account equipment ageing factor and contain reliability parameters calculated with 15 years prediction. Comparison of results obtained by mentioned models was made with the purpose to check influence of ageing on priorities of modernization activities.

Results of modernizations prioritizations is presented in Table 1. Each modernization activity could be related both to the IE contribution (IE) and to specific system importance (RI). In such cases higher group was assigned as a PSA output information (e.g. for Reliability enhancement of RHR system the IE=3 and RI=2, the final PSA output is considered 2).

Table 1: Summary results of modernization prioritization results using base case PSA and ageing PSA models

Measure	Relevant IE	TECDOC – 640	BASE CASE PSA				AGEING PSA			
			PSA ranking			P	PSA ranking			P
			IE	RI	PSA output		IE	RI	PSA output	
Complex investigation of reactor pressure vessel resource	LOCA	**1**	*1 (45.37 %)*[†]	-	**1**	**I**	*1 (38.33 %)*	-	**1**	**I**
Modification of the spray system	LOCA	**1**	*1 (45.37 %)*	*1*	**1**	**I**	*1 (38.33 %)*	*1*	**1**	**I**
Modernization against sump clogging effect	LOCA	**1**	*1 (45.37 %)*	*1*	**1**	**I**	*1 (38.33 %)*	*1*	**1**	**I**
Evaluation of essential service water system's pipeline breaks in boron room	LOCA	**1**	*1 (45.37 %)*	*1*	**1**	**I**	*1 (38.33 %)*	*1*	**1**	**I**
Modernization of ECCS	LOCA	**1**	*1 (45.37 %)*	*1*	**1**	**I**	*1 (38.33 %)*	*2*	**1**	**I**
Confinement safety valves reliability enhancement	LOCA	**2**	*1 (45.37 %)*	-	**1**	**II(a)**	*1 (38.33 %)*	-	**1**	**II(a)**
Improvement of confinement leak-tightness	LOCA	**2**	*1 (45.37 %)*	-	**1**	**II(a)**	*1 (38.33 %)*	-	**1**	**II(a)**
Installation of remote shutdown panel	LOCA	**2**	*1 (45.37 %)*	-	**1**	**II(a)**	*1 (38.33 %)*	-	**1**	**II(a)**
Verification of the capability of ventilation system for cooling ECCS and spray system after reconstruction	LOCA	**2**	*1 (45.37 %)*	*1*	**1**	**II(a)**	*1 (38.33 %)*	*1*	**1**	**II(a)**
Verification of the capability of ventilation system for cooliing of reliable power supply switchgear	-	**2**	-	*2*	**2**	**II(b)**	-	*2*	**2**	**II(b)**
Reliability enhancement of RHR system	Transient	**2**	*3 (10.78 %)*	*2*	**2**	**II(b)**	*3 (13.91 %)*	*2*	**2**	**II(b)**
Complex PTS evaluation	SLB	**2**	*2 (25.55 %)*	*2*	**2**	**II(b)**	*1 (39.75 %)*	*2*	**1**	**II(a)**

[†] Value in brackets reflects portion of particular IE contribution in overall CDF

Modification of emergency feedwater system	Transient	**1**	*3 (10.78 %)*	*3*	**3**	**III(a)**	*3 (13.91 %)*	*2*	**2**	**II(a)**
Modification of the primary circuit overpressure protection system	Transient	**2**	*3 (10.78 %)*	*4*	**3**	**III(b)**	*3 (13.91 %)*	*4*	**3**	**III(b)**
Secondary side piping reliability assessment	SLB	**3**	*2 (25.55 %)*	*2*	**2**	**III(b)**	*1 (39.75 %)*	*2*	**1**	**III(a)**
Investigation of external grid recovery action in case of LOSP	LOSP	**3**	*4 (1.23%)*	-	**4**	**IV**	*4 (0.28%)*	-	**4**	**IV**
Enhancement of reactor protection system reliability	Reactivity accidents	**3**	*4 (2.26%)*	*3*	**3**	**IV**	*4 (2.29%)*	*3*	**3**	**IV**

4. CONCLUSION

Performed research is devoted to investigation of modernization activities planned at Armenian NPP Unit 2 by means of deterministic and probabilistic considerations. Risk-informed prioritization matrix was proposed in order to assure effective combination of probabilistic and deterministic considerations.

Set of criteria stated in [7] have been used as deterministic indicators. Meanwhile probabilistic considerations have been derived from plant-specific PSA models. For this purpose comprehensive ageing PSA plant-specific model has been developed for Armenian NPP Unit 2 based on the results of time-dependent reliability analysis. An attempt was done to compare results received by application of ageing PSA and base case PSA models.

From obtained results it could be concluded that the overall prioritization profile is quite similar for base case PSA and ageing PSA models. However some differences still exists, particularly measure related to “Modification of emergency feedwater system” has changed priority from III to II. Also sub-priorities of “PTS evaluation” and “Secondary side piping reliability assessment” have been changed with APSA model. It was noted that although APSA model could not significantly change the prioritization of modernizations, it could tune details related to sub-priorities between measures located at the same priority zone.

In addition, results of risk-informed prioritization of modernizations have been compared with the results of research performed for systems ranking purposes [6]. Comparison shows that advantages of Ageing PSA application are more strongly marked for system/component level application rather than for such global tasks like modernization prioritization. Summarizing mentioned research studies it is necessary to stress that application of Ageing PSA model allowed analysts to have broader view to the safety issues for considered NPP. Incorporation of ageing aspects in PSA models could reveal aspects which were hidden from analyst in base case PSA model. Having both results of current situation and prediction of risk profile analyst receive a chance to construct more precise action plan for the future.

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