EXTREME EVENT ANALYSIS – A BENCHMARKING STUDY AT ARMENIAN NUCLEAR POWER PLANT TO EXAMINE PLANT ROBUSTNESS AGAINST THE IMPACT OF EXTREME EVENTS

Manorma Kumar[1], Shahen Poghosyan[2], Sos Sargsyan[3], Ola Bäckström[1], Anders Olsson[1]

[1] *Lloyd's Register: Sweden, manorma.kumar@lr.org*
[2] *Nuclear and Radiation Safety Center (NRSC), Armenia*
[3] *Armenian Nuclear Power Plant – Reliability Laboratory, Medzamor, Armenia*

The Fukushima Daiichi accident (Japan, March 2011) revealed the gaps in safety assessment methods and highlighted the need to develop complementary safety assessment methodologies and tools to evaluate the impact of extreme events on nuclear power plants. Considering the existing safety assessment methods, Lloyd's Register Consulting developed a value added tool (the RiskSpectrum® Extreme Event Analyzer (EEA)) to systematically analyze the accident scenarios which are not explicitly addressed in the design extension conditions using integrated deterministic and probabilistic approaches. The tool is based on Fault Sequence Analysis (FSA) methodology developed by International Atomic Energy Agency (IAEA) and verified by application on Goesgen-Daeniken NPP (Switzerland) and Armenian NPP (Armenia). This paper is based on the benchmarking study "Extreme Event Analysis – an application of RiskSpectrum EEA at Armenian NPP" performed under co-operation project between Lloyd's Register Consulting, Nuclear and Radiation Safety Center and Armenian Nuclear Power Plant (ANPP). The purpose of the study was to perform a comprehensive and systematic assessment of robustness and vulnerability of the plant against the impact of extreme events using EEA tool. In general performed investigation allowed to conclude that FSA method and RiskSpectrum EEA are useful and efficient tool for complementary safety analysis.

I. INTRODUCTION

The conventional safety assessment methods i.e. Probabilistic Safety Assessment (PSA) and Deterministic Safety Assessment (DSA), which is used complementary to each other, provide comprehensive and detailed information on plant design including the system dependencies. However in few scenarios for instance combination and correlation of external hazards the PSA/DSA results might not be sufficient to demonstrate the response of the Nuclear Power Plant (NPP) in such extreme conditions. The accident that occurred in Japan at the Fukushima Daiichi NPP on 11 March 2011 highlighted the need to examine more thoroughly the impact of extreme events on nuclear facilities with the specific focus on combination and/or correlation of external hazards.

To support the safety assessment, Lloyd's Register in co-operation with the IAEA developed a bespoke tool (the RiskSpectrum® Extreme Events Analyzer) which is based on the IAEA FSA method [1]. RiskSpectrum EEA, which provides a new, systematic and now proven approach to examine the NPP robustness against the impact of extreme events – beyond the 'Stress Test' exercises post the Fukushima accident. The aim of EEA is to evaluate the robustness of the NPP against the design extension conditions using an integrated deterministic and probabilistic assessment approach. This approach of integrating deterministic and probabilistic analysis overcame a weakness within Stress Test approaches which did not consider 'combinations' of events impacting and aggravating the overall impact of an Extreme Event[i] such as happened at Fukushima. The EEA is an enhanced version of the IAEA FSA concept in terms of tool design and quantification which removed the theoretical weaknesses of the FSA method. The EEA was applied at Armenian NPP to systematically analyze the accident scenarios not explicitly addressed in the Stress Tests or design extension conditions.

This paper presents the results of co-operation project [2] [3] between NRSC, ANPP and Lloyd's Register aimed to apply RiskSpectrum EEA on the Armenian NPP PSA model. The following activities were implemented within the project:

1) development of a plant sample model in RiskSpectrum EEA and FAST-EE (IAEA tool for FSA application),
2) calculation of specific analysis cases and
3) benchmarking of the results obtained by RiskSpectrum EEA and FAST-EE.

II. METHODOLOGY FOR EXTREME EVENT ANALYSIS

II.A. General Approach for Extreme Event Analysis

The overall methodology used for this study refers to the FSA method [1] developed by IAEA within an extra-budgetary project funded by Norway which was then used for development of EEA module for RiskSpectrum. The main objective of the FSA method is to assess plant protection against extreme events focusing on the assessment of the available safety margins at NPP remaining after the events had occurred. Generally, the analysis method is aimed at estimating the robustness of relevant safety systems and the continued presence of the defence-in-depth principle for load cases that exceed the design basis. The method used for analyzing accident scenarios leading to core damage has been named 'The Fault Sequence Analysis (FSA) Method' [1], [4]. In this method, critical failure combinations of the components, structures and human actions leading to core damage are analyzed. Specifically, the method focuses on the analysis of minimal cutsets generated in the PSA. Therefore, a minimum prerequisite for the use of the FSA method is the availability of a Level 1 internal initiating events PSA of high technical quality and sufficient level of detail. The logical models constructed in Level 1 internal initiating events PSA identify the fault sequences that start from a potential initiating event and proceed to core damage through possible failures of mitigating systems and components. These logical models in Level 1 PSA have already taken account of:

- The safety functions of criticality control and residual heat removal
- Accident mitigating possibilities
- Dependencies between systems performing safety functions (front-line systems, support systems)
- Required operator actions.

Therefore, the PSA's logical models can be used to analyze the fault sequences that could occur due to extreme event and could successfully be used as a basis for FSA method application. The method comprises five major analysis steps illustrated in Fig. 1, which shows FSA method result in identification of measures to improve the plant safety based on systematic evaluation of the information already available at the plant (in most cases). Although experience has shown that implementation of FSA method could highlight necessity for additional in-depth analyses that were not performed at the plant before [5]. The FSA method initially was applied for Armenian NPP Unit 2 within the IAEA extra-budgetary project using FAST-EE software [1], [4] and then using RiskSpectrum EEA module [2], [3]. In order to ensure possibility to perform comparative analysis, the application of RiskSpectrum EEA module was implemented using the same principles as it was done for the FAST-EE software [6].

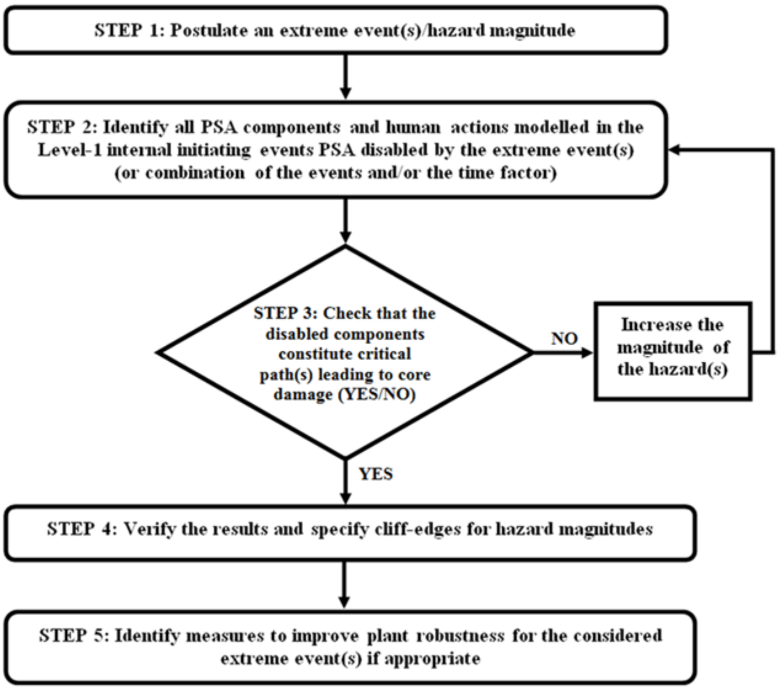

Fig. 1 - Fault Sequence Analysis Steps [1],[5]

II.B. Application of IAEA FSA method in RiskSpectrum EEA

RiskSpectrum EEA is based on IAEA FSA method; however it is an enhanced version of the IAEA FSA concept in terms of tool design and quantification which removed the theoretical weaknesses of the FSA method. RiskSpectrum EEA is directly interfaced with RiskSpectrum PSA, therefore instead of minimal cutsets (MCSs) (as used in the FSA method), a list of safety important components i.e. basic events are directly taken from PSA model, together with design operability limits for safety important components from deterministic analysis and list of site-specific hazards are utilized. By using these inputs, analysis is performed by re-quantification of PSA model either for a selected individual hazard or selected combination of hazards. The EEA application is based on investigation of a plant-specific PSA model and support systems, structures and components (SSCs) and their susceptibility limits against extreme events. The EEA method is illustrated below in Fig. 2. Analyses of these cases are defined with the aim to be able to identify:

- values of individual hazards which are critical for NPP design and
- combinations of external hazards which could lead to core damage.

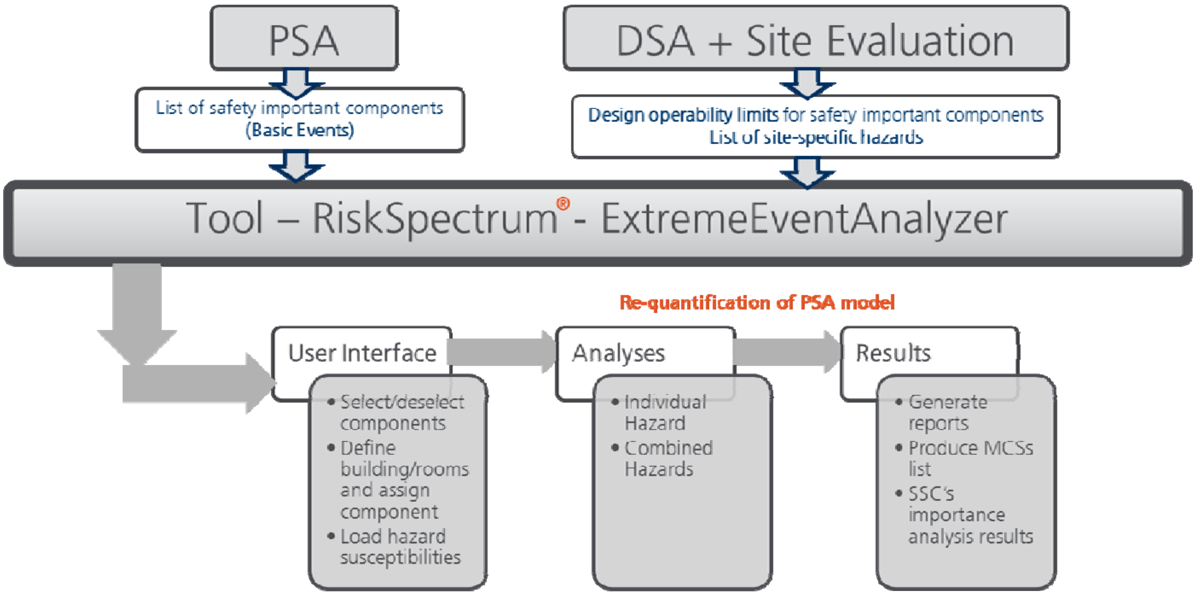

Fig. 2 – RiskSpectrum EEA Method [7], [8]

II.C. Analysis Implementation Steps in the FSA/EEA Method

The process of FSA/EEA method application implies the following steps [2], [6]:

1. Selection of external hazards for further consideration
2. Verification of PSA model quality from the point of view of FSA/EEA method application
3. Data collection
4. Input deck development for FSA/EEA method application
5. Implementation of calculations
6. Interpretation of results

II.C.I. Selection of external hazards for further consideration

The process of FSA method application started with the selection of external hazards for further consideration. The selection of hazards was implemented based on already performed studies (e.g. external hazards PSA [9], ANPP stress-test report [10], etc.). The existing safety assessments of Armenian NPP Unit 2 contain external hazards screening stage, which is based on following screening criteria:

A. Screening of external hazards which are not applicable for ANPP site
B. Screening by impact
C. Screening by frequency

During the project implementation the criteria B was not applied because it was noted that hazards screened out using criteria B could be dangerous in combination with other events which will be analysed using FSA method. Also the criteria C was not applied taking into account that FSA method does not deal with hazard frequencies. Thus, the overall list of external hazards was revisited in order to compile the list of applicable natural hazards. Finally it was concluded that following hazards can be challenging for plant safe operation:

- Seismic
- Heavy rainfall
- High winds
- Wind-induced missiles
- Dust storm
- High temperatures
- Low temperatures
- Snow load

In addition to the mentioned list the prolonged duration of accident was also considered as a hazard.

II.C.II. Verification of PSA model quality

Once the list of hazard is selected, the PSA model was checked from the point of view of FSA method application. Verification of PSA model's capabilities allowed to reveal certain deficiencies in existing ANPP PSA model which creates obstacles for efficient application of FSA method. Therefore special efforts were devoted for additional supporting analysis (e.g. elimination of over conservatism in Loss of Off-Site Power (LOSP) accident progression model) and corresponding PSA model upgrade[1] [6].

II.C.III. Data collection

Adjustment of PSA model allowed to finalize list of PSA element (equipment) which is used for further analysis. List of PSA elements includes basic events which represent equipment failures, human errors and Common Cause Failures (CCFs). The next step implied identification of operability limits (susceptibility limits) for each PSA element in the list. Data collection for operability limits was performed based on plant walk-downs, design documentation, available safety assessments and expert judgment. During data collection, it was identified that some information is not available and additional analytical support is required (analysis of plant ventilation system's failure impact, analysis of feasibility to perform certain human actions in case of external hazards, etc.). Data collection was performed for selected external hazards and about time related cliff edges in terms of components operability. For effective data collection special checklists were developed for specific external hazards. Thus for example for flooding of rooms and buildings checklists of the given type of external impact contain the following data and parameters for accurate and quick data collection [6]:

- List of equipment and elements of PSA system
- List of rooms and buildings in which the equipment in located
- Relative level of equipment and elements located in the rooms and buildings, where the minimum levels of critical contact with the water was taken as a base
- Zero elevation in rooms and buildings
- Geodetic level of rooms
- Possible ways of water penetration into rooms and building

For high and low temperatures the following data parameters were required for analysts to be able to identify electrical components operability in case of ventilation systems failure.

[1] This activity was performed within IAEA extra-budgetary project on FAST-EE application for Armenian NPP Unit 2 [6]. Results of the activity were directly used within this study.

- List of PSA model equipment rooms
- Geometrical data of the rooms (length, width, height, wall thickness)
- Type and characteristics of structures
- Equipment total heat output in rooms
- Description of rooms design peculiarities (door and window area, constructive interrelation, common part)

Data for seismic events, high winds (including wind-induced missiles and dust storms) and snow load have been taken from plant design documentation, available safety studies (e.g. seismic PSA) or based on expert judgment. For time related cliff edges, following types of equipment were considered:

- Equipment with high failure rate which could fail within short time of operation, and
- Equipment with certain limitations related to fuel capacity, water amount, batteries discharge time, etc.

II.C.IV. Input deck development

Detailed data collection and identification of operability limits for PSA elements allowed to finalize input deck for FSA/EEA method application [6] [2]. Identical input decks were created for FAST-EE and RiskSpectrum EEA software. Basically created input decks implies the following attributes:

- Assignment of basic events to the plant buildings
- Basic events' and plant buildings' operability limits defined for each external hazards
- Linking of above mentioned information with minimal cut-sets.

In addition following general assumptions were applied during input deck development:

- Only power operation mode of ANPP is considered
- It was assumed that external hazards are directly leading to loss of off-site power
- No credit is given for recovery actions aimed to restore off-site power supply. This assumption is mainly done for evaluation of importance of recovery actions and identification of accident scenarios when off-site power supply recovery action is critical. As a result no credit was done to R4H basic event.
- Increase of dust concentration in the air and wind induced missiles were assigned to wind speed values
- Fuel of diesel generators located outside of Diesel Generator (DG) building was not taken into account. This conservative assumption is made due to the fact that external hazards could create obstacles for fuel supply to DGs.

II.C.V. Implementation of calculations

After finalization of input deck several analysis case were defined for further investigation. Analysis cases were defined with the aim to be able to identify:

- values of individual hazards which are critical for ANPP design
- combinations of external hazards which could lead to core damage

Possible interaction between different hazards/factors is shown in Table 1 [2]. As it is presented in Table 1 some of the combinations are not physically possible due to nature of external hazards (e.g. snow load and high temperature). Based on the results of already performed study [6] and taking into account lessons learned from Fukushima accident it was decided to focus on possible combinations of seismic and flooding hazards. The list of performed analysis cases is presented below:

1. Dust storm with wind speed 33 m/s
2. Heavy rainfall with flooding level 10 cm
3. Seismicity 0.18g
4. Seismicity 0.18g and heavy rainfall with flooding level 10 cm
5. Seismicity 0.19g
6. Seismicity 0.19g and heavy rainfall with flooding level 10 cm
7. Seismicity 0.15g and high ambient temperature 32°C

Table 1. Possible combinations of considered hazards/factors

	Seismic	Heavy rainfall	Dust storm	Snow load	High temperature	Low temperature	High wind	Wind induced missiles	Cliff-edge effect, time (hours)
Seismic		x	x	x	x	x	x	x	x
Heavy rainfall	x						x	x	x
Dust storm	x				x		x	x	x
Snow load	x					x	x	x	x
High temperature	x		x				x	x	x
Low temperature	x			x			x	x	x
High wind	x	x	x	x	x	x		x	x
Wind induced missiles	x	x	x	x	x	x	x		x
Cliff-edge effect, time (hours)	x	x	x	x	x	x	x	x	

For each of mentioned analysis case several calculations were performed using both RiskSpectrum EEA and FAST-EE tools [2] in order to find critical values of external hazards leading to plant core damage. The attempt was done to reveal lowest magnitude events that could be challenging for ANPP safety. Details about calculation results and insights are presented in next sections IV and V.

III. ANPP PSA MODEL

III.A. Development of a Sample Model

NRSC and ANPP created a realistic sample model that is based on the plant real PSA model [2] [3]. The real PSA model was modified moderately, sufficiently so that it is not jeopardizing the ANPP safety and security. The main principle that was implied is that the sample PSA model shall contain the ANPP full scope RiskSpectrum PSA model, moderately modified the RiskSpectrum EEA model data. In order to assure this the fault tree and event tree structure and analysis cases related to the extreme event analysis were kept as realistic as possible when it comes to modelled SSCs, logic and level of detail. Changes introduced are mainly related to reliability data, susceptibility values and ID or descriptive fields. The model logic and level of detail are kept as realistic as possible (see Fig. 3). Also, some additional PSA modelling is completed to include the impact of extreme temperature considerations on HVAC systems (see Fig. 4).

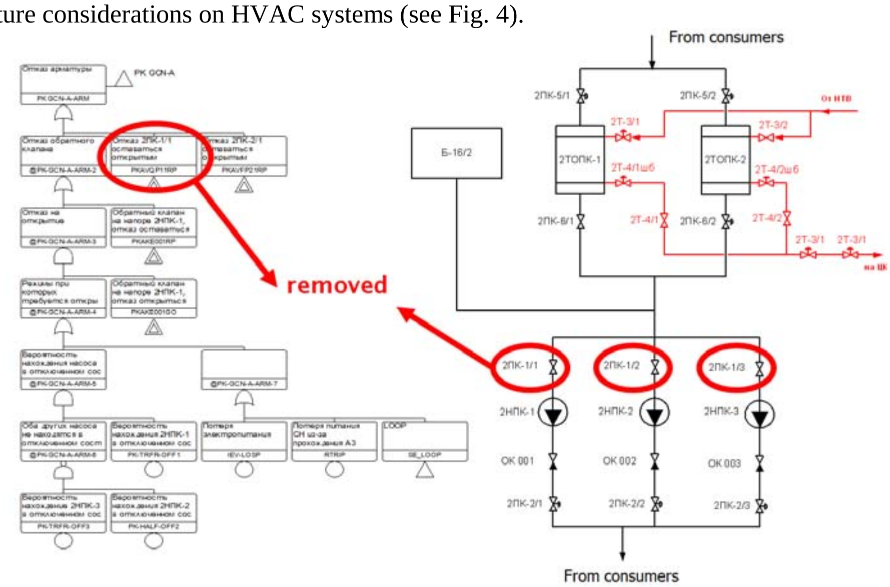

Fig. 3. Example for simplification of fault trees in sample PSA model [2]

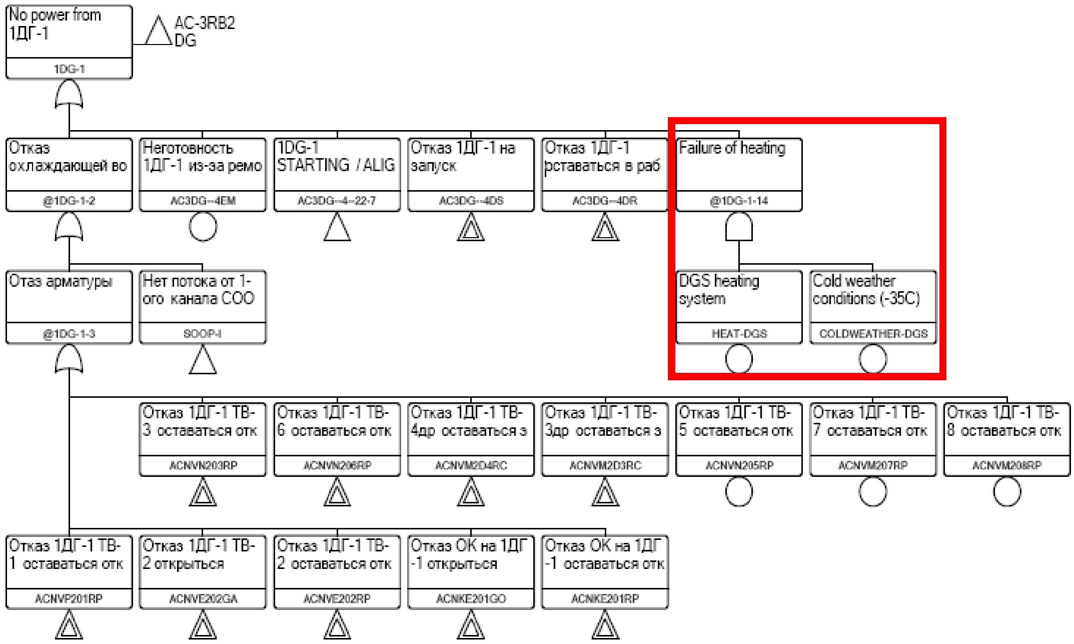

Fig. 4. Example for additional PSA modelling to consider extreme temperature [2]

III.B. PSA Model and Systems related to Loss of Off-Site Power

ANPP design is based on the first generation of VVER-440/V-230 reactor – seismically reinforced design VVER-440/V-270. This design has additional seismic protection features, such as seismic reactor cooldown system [9] [2]. Safety features are designed as two train systems. Several systems could be dedicated for the same safety function (e.g. there are four systems to provide feed-water to secondary side, see Fig. 5). The success criteria is in general operation is 1 out of 2 trains.

Loss of off-site power event is an event which leads to unavailability of power supply from the plant to grid and vice-versa. The loss of off-site power event implies assumptions that normal power supply is not available and DGs are still available (failure of DGs means station blackout). The ANPP electrical system contains two independent channels, where components are divided by three categories, see Fig. 6. First category (shown in RED color in Fig. 6) consists of components that could be supplied from DC batteries, DG and normal power supply. Second category (shown in BLUE color in Fig. 6) consists of components that could be supplied from DG and normal power supply. Third category is non-reliable category (shown in BLACK color in Fig. 6) which consists of components that could be supplied only from normal power supply. The concept of loss of power impact on safety systems is shown in Fig. 5. The main safety functions related to core cooling could be implemented by different two-train systems mainly aimed to [2]:

- Control pressure in primary or secondary circuits
- Feed primary or secondary circuits
- Provide support for frontline system.

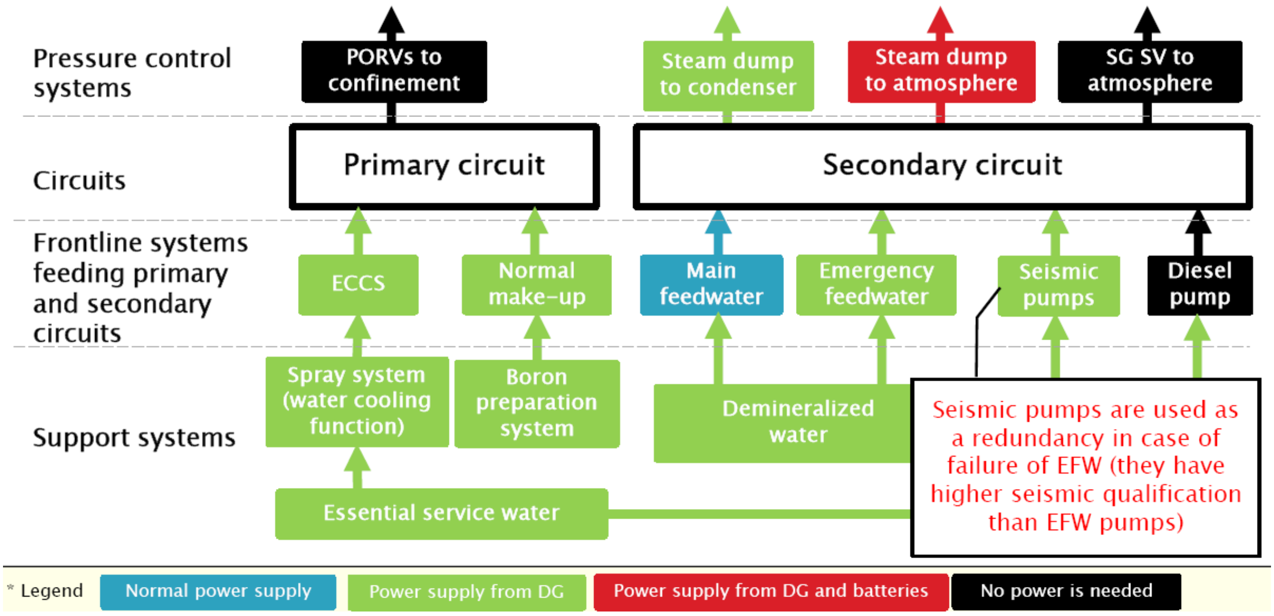

Fig. 5. Concept of loss of power impact on safety systems [2]

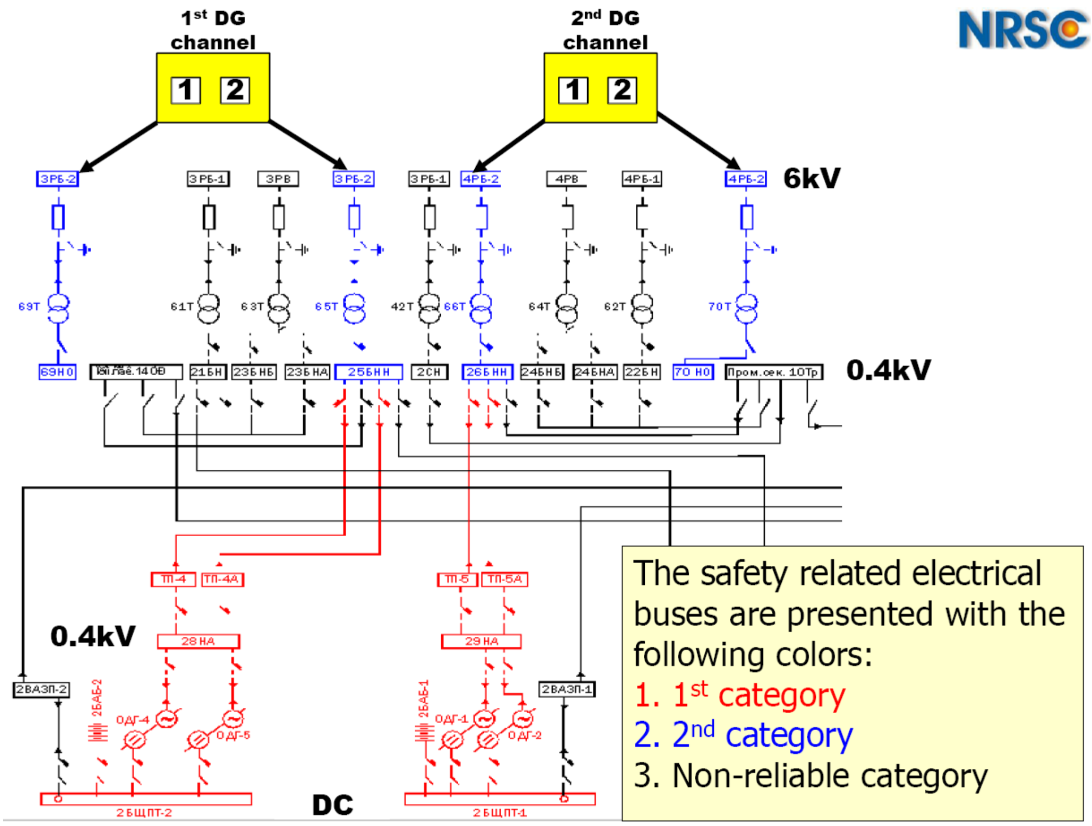

Fig. 6. System related to LOSP and Electrical system categories [2]

IV. BENCHMARKING BETWEEN RISKSPECTRUM EEA AND IAEA FAST-EE

The sample model created as a result of simplifications has been applied both for FAST-EE and RiskSpectrum EEA software [2]. Same susceptibility values have been applied in the input decks created for both software. Models created by FAST-EE and RiskSpectrum EEA were analysed for hazards and combination of hazards selected. The overall results of calculations are summarized in Table 2 [2] [11] (see below). The discussion of results presented in Table 2, relevant conclusions and observations are presented in the last conclusion section V.

Table 2 Summary results of benchmarking between RiskSpectrum EEA and FAST-EE [11] [2]

Analysis cases #	**Hazards**	**Value**[2]	**Combination (Yes/No)**	**Results- MCS generated**		**Remarks**
				EEA	**FAST-EE**	
1	Seismic	0.18g	No	32	32	OK, similar results
2	Seismic	0.19g	No	56	32	Additional sequences generated by EEA
3	Flood	10 cm	No	32	No results	Additional sequences generated by EEA
4	High temperature	+43°C	No	2	No results	Additional sequences generated by EEA
5	Dust storm	33 m/s	No	36	No results	Additional sequences generated by EEA
6	Seismic	0.19g	Yes	56	32	Additional sequences generated by EEA
	Flood	10 cm				
7	Seismic	0.18g	Yes	32	32	OK, similar results
	Flood	10 cm				
8	Seismic	0.19g	Yes	56	2	Additional sequences generated by EEA
	High temperature	+32°C				

V. CONCLUSIONS

Lloyd's Register benchmarking study showed that EEA and the IAEA case-studies led to similar results in terms of the technical logic of MCSs generated for each analysis case. The additional sequences identified through the EEA approach (according to the results presented in Table 2) were valid combinations that should have been taken into account. FAST-EE software is designed to work with limited number of MCSs generated by the PSA model [4]. The EEA directly interfaced and was compatible with ANPP RiskSpectrum® PSA model and assured that the entire model was included in the evaluation of the overall events analysis (as single as well as combinations of events). The EEA results included the hazard threshold for individual as well combination of hazards and analyses were produced for the SSC's that could be affected by extreme events. This benchmarking study gave the evidence to conclude that FSA method and EEA combined is useful and efficient tool for complementary safety analysis. In summary, the Lloyd's Register benchmarking study demonstrated that the EEA (RiskSpectrum® Extreme Events Analyzer) is a superior approach to any existing methodologies as it identified all potential critical scenarios.

ACKNOWLEDGMENTS

The authors would like to thank Ms. Irina Kuzmina, IAEA Safety Officer; Mr. Artur Lyubarskiy, the former IAEA Safety Officer and Dr. M. El-Shanawany, the former IAEA Senior Safety Officer for their encouraging support and valuable technical contribution in development of RiskSpectrum EEA tool and using IAEA FSA method.

[2] Presented values are derived based on the non-realistic susceptibility values used for this benchmarking study. The real susceptibility values were modified in the frame of sample model development. Presented values do not reflect real robustness of ANPP. Presented values have been used for verification of RiskSpectrum EEA, benchmarking with FAST-EE and RiskSpectrum EEA capabilities demonstration purposes.

REFERENCES

[1] I. Kuzmina, A. Lyubarskiy, M. El-Shanawany, "An Approach for Systematic Review of the Nuclear Facilities Protection against the Impact of Extreme Events", *Proceedings of the Nordic PSA Conference – Castle Meeting 2011*, Stockholm, Sweden, 5-6 September 2011.

[2] Lloyd's Register, "Extreme Event Analysis – Joint research and development project – an application in Armenian nuclear power plant", Sweden, 19th January 2016.

[3] Joint research and development project agreement between Lloyd's Register Consulting – Energy AB, Nuclear and Radiation Safety Center and CJSC Haykakan Atomayin Electrakayan for the Joint Research and Development Project to apply RiskSpectrum EEA on the PSA model at the Armenian Nuclear Power Plant, 31 October 2014.

[4] User Manual, Version 2.2, ACCESS-Based Software 'Fault Sequence Tool For Extreme Events (FAST-EE)', IAEA Extrabudgetary Programme NOR, Norway, May 2014.

[5] I. Kuzmina, A. Lyubarskiy, P. Hughes, J. Kluegel, T. Kozlik, V. Serebrjakov, "The Fault Sequence Analysis Method to Assist in Evaluation of the Impact of Extreme Events on NPPs", *Proceedings of the Nordic PSA Conference – Castle Meeting 2013*", Stockholm, Sweden, 10-12 April 2013.

[6] G. Kanetsyan and S. Poghosyan et al., "Application of the fault sequence analysis method for the Armenian NPP: Results and insights from the benchmarking study performed under an IAEA's extra budgetary project", *International Topical Meeting on Probabilistic Safety Assessment and Analysis (PSA2015 Conference)*, Sun Valley, Idaho, USA, 26-30 April, 2015.

[7] M. Kumar, "Evaluation of the Impact of Extreme Events on NPPs", Presentation to EDF Energy, UK, December 10, 2013.

[8] M. Kumar et. al., "Tool for Extreme events analysis", *IAEA Technical Meeting July 7-11*, Vienna, July 2014.

[9] Probabilistic Safety Assessment Level 1 of Armenian NPP. External hazards. Book 2 – Detailed analysis, Nuclear and Radiation Safety Center, Yerevan, 2004.

[10] Stress-test self-assessment report of the Armenian NPP, Medzamor, 2014.

[11] M. Kumar et. al., "Systematic approach to examine nuclear power plant robustness against the impact of Extreme Events – a case study at Armenian nuclear power plant", *Proceedings of the Nordic PSA Conference – Castle Meeting 2015*", Helsinki, Finland, 8-10 September 2015.

[12] INTERNATIONAL ATOMIC ENERGY AGENCY, Extreme external events in the design and assessment of nuclear power plants (IAEA-TECDOC-1341), March 2003, Vienna.

---

[i] **Note:** an 'Extreme Event' is meant to be an event providing a widespread damage to the NPP; it could be caused by an individual hazard or combined hazards not explicitly included in the design basis, examples are natural or man-induced hazards of the magnitudes higher than the design basis. [12]