ACCIDENT SEQUENCE PRECURSOR ANALYSIS IN CZECH REPUBLIC

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Precursor analysis based on PSA is widely used in nuclear power industry to judge the significance of events to safety. A brief history of the use of the PSA application in the evaluation of operating events in the Czech Republic is the subject of this paper. It presents the scope and appropriateness of the PSA models of NPP Dukovany and NPP Temelin for precursor analysis. At the end an example of the precursor analysis of the real selected event from VVER operational history is presented.

I. INTRODUCTION

Employees of ÚJV Řež participate for a long time on analysis of events at NPP power plants in the Czech Republic. They cooperated on a deterministic assessment of operational events at Dukovany in the past and output of this activity served as an annual independent assessment of operational events at the power plant for the needs of the regulatory authority of SONS (State Office for Nuclear Safety).

Since 1986 the Reliability and Risk Department devoted systematic care towards development of methodologies for probabilistic risk analysis and PSA model for NPP Dukovany. In addition, department staff cooperates on development of the PSA model for NPP Temelin. In the first half of the 90's the development of its own software for probabilistic risk assessment has been terminated and commercial software Risk Spectrum from RELCON (now Lloyd's Register) was obtained.

With the gradual use of the PSA model for various applications around since 2001 the activities have been initiated with goal of creating a basis for probabilistic assessment of the events that occur during the operation of the NPP. Due to good relations with the staff of the Operational Experience Feedback (OEF) department, and prior knowledge of the deterministic assessment of operational events, the access to detailed information from NPP Dukovany is relatively easy.

The USA experience has been used during searching of our own approach to probabilistic assessment of selected events, and on this basis own methodology for probability risk analysis of events has been developed in 2002. Based on this methodology and other current information the analysis of the Accident Sequence Precursor (ASP) is currently carried out for the NPP Dukovany, but recently also for NPP Temelin.

II. HISTORY OF ASP ANALYSIS IN THE CZECH REPUBLIC

ASP analysis based on PSA is widely used in nuclear power industry to judge the significance of events to safety. This typically involves evaluating the effect on plant risk caused by known influence of real or potential initiating event or unavailability of equipment.

The ASP analysis activities started at NPP Dukovany in 2002 applying information from USA[1] to selection of risk relevant events from NPP operational history and detailed risk analysis of selected events. The general aim was implementation of risk based approaches and employing the most current status of already developed Probabilistic Safety Assessment (PSA) models of NPPs operated in Czech Republic in support of activities of Czech Nuclear Regulatory Body (SUJB).

After the first pilot study carried out in 2002, the original methodology for probability risk analysis of events based on worldwide state-of-the-art was developed[2]. This methodology describes in detail the individual steps of the analysis and the ASP is now performed in the Czech Republic with its use.

Initially, the ASP analysis was not carried out on a regular basis. ASP evaluation was performed on ad hoc request of SUJB or NPP in next few years until 2010. During 2000-2010, the use of probabilistic risk assessment methods gradually gained the reputation in both the Czech Nuclear Authority, as well as on the NPPs (the obligation to use of PSA is not fixed in Czech Republic by Atomic Act - this obligation will be established by the new law, which will be in effect from 2017). In 2010, regular activities of ASP analysis of the potentially risk related events occurring at both Czech NPPs (Dukovany and Temelin) started, and have been running each year up to now. Typically, several levels of screening of events have been performed and few events have been selected for detailed analysis by means of PSA model, including what-if analysis of a number of possible alternative scenarios. The results have been also presented in international projects and meetings, for example during Technical Meetings on Experience with Risk-based Precursor Analysis, which have been held by GDF-Suez in Brussels every year.

III. Resources for analysis of ASP – PSA model

III.A. Using the PSA model

The role of the PSA in the context of processes occurring at the NPP Dukovany is defined in detail in the documentation Rules – Probabilistic safety assessment[3]. PSA is generally used to support safety management, to support the decision making processes during normal operation and also during shutdown and finally to evaluate the total risk of the NPP operation. Specifically, it is used for the following applications and purposes:

- assessing the operation safety (risk) level,
- **analysis of the operating events severity from the operational history and also from the hypothetical conditions that could occur (ASP),**
- detecting of the NPP weaknesses and corrective actions proposing,
- assessing of proposed equipment modifications which are designed for nuclear safety improving,
- evaluation of the changes in the operating procedures,
- evaluation of the equipment testing intervals and allowed periods for the systems unavailability,
- risk profiles monitoring of the real NPP configurations by the Safety Monitor software (monthly reports, monitoring and risk profiles during online maintenance, biannual profiles for the SONS, annual risk reports of the all units operation, etc.),
- risk-informed evaluation of all shutdowns,
- identification of the risk dominant accident scenarios or the NPP units configurations,
- support of periodic safety reviews.

At the NPP Dukovany, PSA is used as an important complement to the deterministic safety assessment. Especially in cases where the deterministic safety evaluation is not able to quantify the rate of nuclear safety (operational risk) increase/decrease.

III.B. Quality of the PSA model

III.B.1. Scope of the PSA

Initiating events

The current PSA study for the NPP Dukovany includes:

- Internal events - all the NPP technology failures or system malfunction due to human error or computer software are included.
- 400 kV circuit breaker failure and loss of offsite power (LOSP) are also included in the internal events. It is in accordance with the IAEA SSG-3 instructions[4].
- Internal hazards - internal flooding, internal fires, heavy loads falls and missiles in the turbine hall and in the longitudinal auxiliary floor are included.
- External hazards – external events due to human error and external events caused by the extreme nature activities, including seismic events (for the 1st unit), are included.

Modes of operation

PSA study for the NPP Dukovany analyzes the average risk for the groups of initiating events (IE) in the following modes of operation (Level 1 and Level 2 PSA):

- nominal power operation (Mode 1)
- low power and shutdown states operation and hot reserve conditions (Mode 1 at reduced power and Modes 2 and 3)
- planned and unplanned outage (Modes 4 to 7)
- Modes 1 to 7 are represented by 14 plant operational states (POS) in PSA model

Differences between individual units

Current PSA study for the NPP Dukovany includes models for odd and even unit. It takes into consideration and evaluates quantitatively significant differences between individual units (i.e. between the 1st and 3rd unit, respectively between the 2nd and 4th unit).

III.B.2 Level of the PSA details

The Level 1 PSA is conducted for a full scope of internal and external IEs for all modes of the NPP operation. The Level 1 PSA documentation is then processed in a scope and structure according to the instructions of IAEA and State Office for Nuclear Safety and also in accordance with the ČEZ procedures.

The Level 2 PSA is also processed for a full scope of internal and external IEs for all modes of the NPP operation.

III.B.3 Technical adequacy of the PSA

The PSA study for the NPP Dukovany was subjected to IPERS revision in 1998 and IPSART revision in 2016. These missions were carried out by the IAEA teams which consisted of professionals from the USA, Spain, Great Britain, Hungary, Russia, Switzerland, Ukraine, and Armenian. Revision conclusions showed the high professional level on the entire PSA study processing and also positively evaluated the approach which the NPP Dukovany uses in the risk assessment. All recommendations were analyzed in detail and accordingly incorporated during the following Living PSA development.

The PSA study for the NPP Temelin was subjected to IPERS revision in 1997 and IPSART revision in 2003. The next IPSART revision is planned in close future.

In 2005, the PSA studies at both NPPs were subject to revision by external company ENCONET at a request of the State Office for Nuclear Safety. The aim of this revision was to determine the suitability of the study and models for the PSA applications. It was stated that the study and the NPP Dukovany and NPP Temelin models (for all modes of operation) are an appropriate basis for the PSA applications.

III.B.4 PSA maintenance and updates

The Level 1 PSA model is regularly updated every 1-2 years and the following changes are included especially:

- project and equipment modifications,
- procedures changes
- equipment testing changes (e.g. testing intervals changes),
- changes in the equipment maintenance (if they affect the PSA model),
- results of new analyzes or other factors that relate to the PSA.

The Level 2 PSA models are updated as needed. Their last revision and update (including the inclusion of extreme external events caused by natural hazards) was made in 2015.

Initiating event frequency, basic events data and other input data are updated once per every 5 years.

These types of data are updated regularly:

- specific component reliability data based on the data collection from the NPP Dukovany events,
- unavailability parameters due to maintenance and testing based on the specific information for the NPP Dukovany,

- POSs lengths based on the operating history records,
- IEs frequencies based on the specific data for the NPP Dukovany database,
- IEs frequencies and other events based on the generic data (if there are no specific data from the NPP Dukovany operation).

If necessary, the data may be updated also in a shorter interval.

Most of the data characteristics are (if possible) primary based on the specific experiences and information from the NPP Dukovany operation. The only data with a very rare occurrence are used in a generic database (data for LOCA IEs, etc.).

There is a number of supporting databases that are used in the NPP Dukovany for collecting of the components events and malfunctions information. For the PSA purpose, information from these specific resources is then frequently used:

- SIS database (reliability information system) – it contains information about all events and safety systems equipment failures and equipment with impact to the NPP operation,
- shift engineer reports,
- operator's operational books (mainly in a electronic form from the reactor unit supervisor)
- ... and several others sources of information

The last regular data update was carried out in 2014. The next update is planned for 2018. Since 2009, the data are stored in a specific PSA database. This database was developed in ÚJV Řež a. s. and was adapted by the operational staff for the needs of data collecting at the NPP Dukovany (and also at the NPP Temelin). The data are distributed to the IEs data frequencies and reliability data of components. Further sorting is done then by assignment of additional characters according to the PSA data models divisions for the NPP Dukovany (and also for the NPP Temelin).

IV. Brief description of the analysis steps

The following paragraphs provide a brief description of the procedure for the ASP. ASP analysis for NPP Dukovany is performed in ÚJV Řez, because the development of the Living PSA model was carried out in this company. PSA model is operated in Risk Spectrum software. ASP analysis at NPP Temelin is carried out in cooperation with the staff from the PSA department at the NPP Temelin because ÚJV Řež does not have the PSA model for this particular NPP (PSA model is developed in NUPRA code).

IV.A. Information about operational events

The most important source of information about events that occurred in the past period in NPP is SIS database. The database contains relevant information about all significant events (in terms of operational risk, nuclear risk, general risk). The protocol for each recorded event contains detailed information about the course of events listing all major time steps.

The event log contains information about the status of the block before the occurrence of the event, the safety aspects of the event and assessment of the seriousness of the event according to the international INES scale.

The final summary assessment provides a description of circumstances of the event (failure mechanisms, activities of personnel, organizational factors, external factors) that led to the initiating of the event. It includes an analysis of the direct causes and root causes of the event and the related corrective measures. It is clear that not all events could potentially cause damage to the core and that is why the selection of them is performed.

IV.B. Screening of events

Screening of the events is conducted in two rounds and its aim is eliminate the events that are not possible or necessary to analyze in detail as ASP.

Qualitative screening is carried out in the first round where the following events are excluded from further analyzes:

- the events with operational and/or organizational character that have no impact on nuclear safety
- the events with obviously negligible risk
- the events that cannot be evaluated by PSA model (for example exposure of a workers during maintenance or due to weakness in PSA model - e.g. missing thermohydraulic assessment, etc.)

A simplified quantification of the potential impact of events on the CDF is performed in the second round. The events with unclear information for ASP analysis are discussed in detail with OEF staff and safety engineers at NPP.

The following indicators are used to evaluate the ASP.

- delta Core Damage Frequency – ΔCDF ($\Delta CDF = CCDF_{(Conditional scenario)} - CDF_{(basic scenario)}$)
- Conditional Core Damage Probability - CCDP ($CCDP = CCDF_{(Conditional scenario)} \times t$)
- Incremental Conditional Core Damage Probability – ICCDP ($ICCDP = \Delta CDF \times t$)

ΔCDF indicates the increase of the instantaneous value conditional of risk as a result of accident scenarios with increased frequency. CCDP expresses conditional probability of an accident, due to effect of certain operational events and ICCDP expresses increment of conditional probability of an accident, due to effect of certain operational events.

The simplified quantitative assessment of risk significance of each event is performed by comparing with a pre-computed risk matrix significance of specific systems that contains values of ΔCDF and ICCDP for various combinations of redundant trains of safety systems. The following table shows the number of events that enter into the screening process and the number of events that were eliminated in each round of this process.

After the second round of screening, there are several events which are candidates for detailed precursor analysis. Due to the limited budget for the implementation of detailed ASP analysis one detailed analysis of selected events is performed annually. The final selection of this event is based on consultation with the staff of SONS (according to the recommendation of UJV Rez or based on SONS interest to analyse specific event).

TABLE I. Number of events and overview of screening process

NPP	Year	No. of events	Screened out in 1st round	Screened out in 2nd round	Potential for ASP	No. of analyzed ASP
Dukovany	2007-2010	627	551	65	11	2
	2011	120	113	1	6	1
	2012	129	120	6	3	1
	2013	107	93	10	4	1
	2014	108	98	4	6	1
	Total	***1091***	***975***	***86***	***30***	***6***
Temelin	2007-2010	1022	973	43	6	2
	2011	224	219	1	4	
	2012	240	233	5	2	
	2013	191	189	1	1	
	2014	187	177	6	4	
	Total	***1864***	***1791***	***56***	***17***	***2***
Duk+Tem	**Total**	**2955**	**2766**	**142**	**47**	**8**

Very simple database (MS Access) was developed in the NRI Rez for the purpose of survey of the events from both NPP and for effective implementation of the events selection for detailed analysis of ASP. This database currently contains thousands of records about events at Dukovany and Temelin for the period 2007-2015. One of the outcomes is a database report that documents the screening process. This document is part of an annual events analysis carried out for SONS. Input form of database with search options is shown in Figure 1.

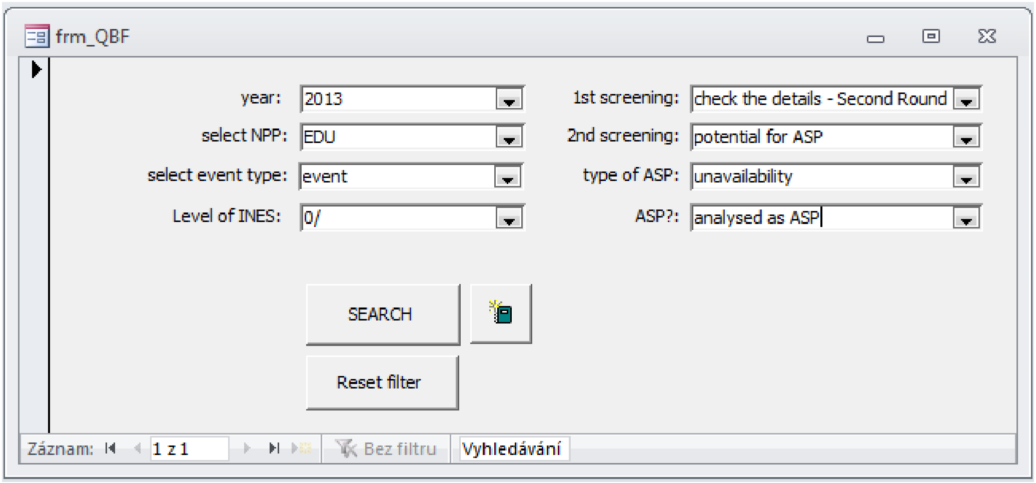

Fig. 1. Main windows of database for record of events from NPP and screening process justification

IV.C. Analysis of selected events

ASP analysis is performed for the selected events using the methodology[2]. The necessary modifications of the PSA model are provided in accordance with this methodology. By the event type (initiating event, potential initiating event, unavailability) the corresponding indicators are calculated and compared with the criteria. The values of criteria for the used indicators are shown in the following table.

TABLE II. Threshold levels for risk level of event categorization

Type of analyzed operational event	Threshold level[1]	Risk level of operational event
Initiating event	CCDP ≥ 1E-6	Accident sequence precursor
	1E-6 > CCDP ≥ 1E-7	Safety significant event
	CCDP < 1E-7	Non safety significant event
a) Potential initiating event	ΔCDF[2] ≥ 1E-6/year and simultaneously ICCDP ≥ 1E-6	Accident sequence precursor
b) Equipment unavailability	ΔCDF ≥ 1E-7/year and simultaneously ICCDP ≥ 1E-7	Safety significant event
c) Potential equipment unavailability	ΔCDF < 1E-7/year and simultaneously ICCDP < 1E-7	Non safety significant event

The final step of the ASP analysis is focused on the "What if" analysis. The most important practical aspects during the implementation of this analysis are:

- What impact this operational event could have on operational risk of unit for different initial situation (in other POSs)?

[1] The numerical values of the significance indicators are determined on the basis of certain foreign practices.
[2] The threshold value for delta CDF is set approximately so that the increase of the instantaneous risks to baseline CDF about ten percent indicates the possibility of ASP.

- What impact this operational event could have on operational risk of unit in concurrence with other failures in particular POS?
- Is there a potential for Common Cause Failure?

V. EXAMPLE OF ANALYSED EVENT AT NPP DUKOVANY

V.A. Description of event

March 28, 2013
The planned test of the Emergency Load Sequencer in the third safety train (ELSIII) was carried out during the morning shift at the second unit of NPP Dukovany. The reactor was at that time in Mode 1 (power operation).

After the start of the Emergency Diesel Generator No. 4 (EDG4) and its connection to the substation 2BX the loads were sequentially connected by the program. An unusual oscillation of ammeters of all connected drives has been found at the control room. Electric engineer informed (8:13) about the need to shutdown EDG4 due to high vibration, noise and fire propagation (burning of oil) into the exhaust area. Electric engineer switched off the EDG4 by pressing the Emergency stop button (8:16). The substation was connected again to the normal supply and drives involved in ELSIII test were transferred back. EDG4 and ELSIII were secured for repair.

The damage of the piston ball bearings, ball pivot rod damage, damage of the piston crown, damage of intake and exhaust valves, corrupted valve tappets and damaged cylinder No.6. were subsequently found. The scope of damage is shown in Figure 2.

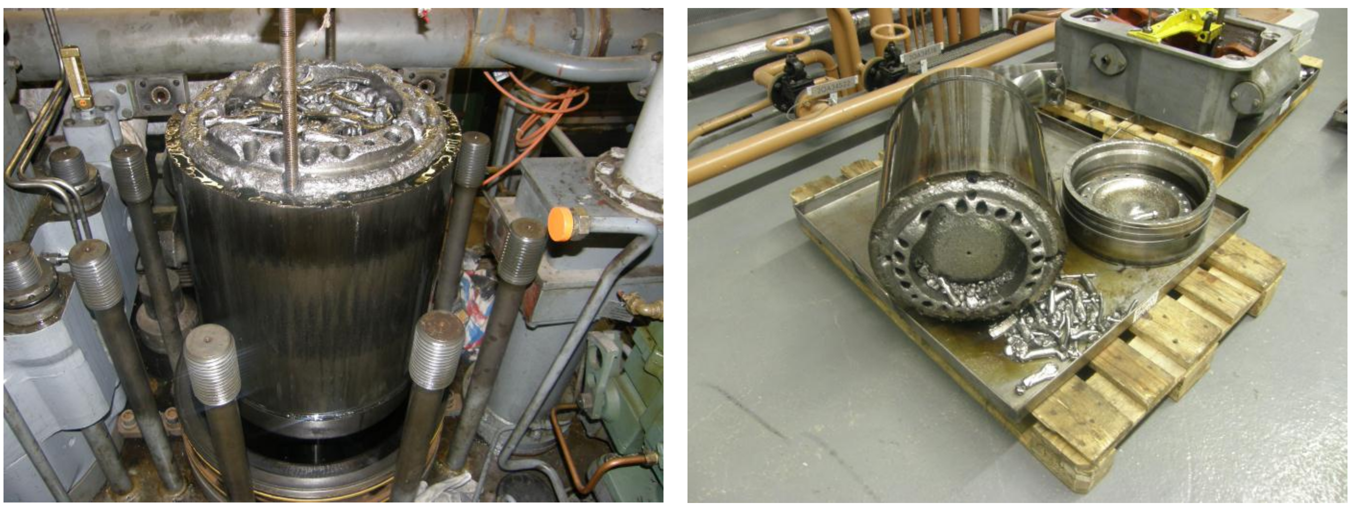

Fig. 2. Damaged piston from 6th cylinder of DG4 after disassembling

V.B. Safety aspects of event

The failure of EDG4 occurred during a planned test of ELS. In terms of nuclear safety it is the loss of one redundant line of the secured power supply of II. category (enter to Limit and Conditions). It is necessary to check the operability of the remaining two lines of the secured power supply of II. category. In the case that a broken line is not put into operation within 72 hours it is necessary to shut down the reactor.

V.C. The course of event

The simplified course of event is presented in Figure 3. The unit was 56 hours with unavailable EDG4 in Mode 1 (full power). During planned shutdown process for refueling the unit went through MODE 2 – 5. The risk of the plant operation was also affected in these Modes. Complete repair took more than 19 days.

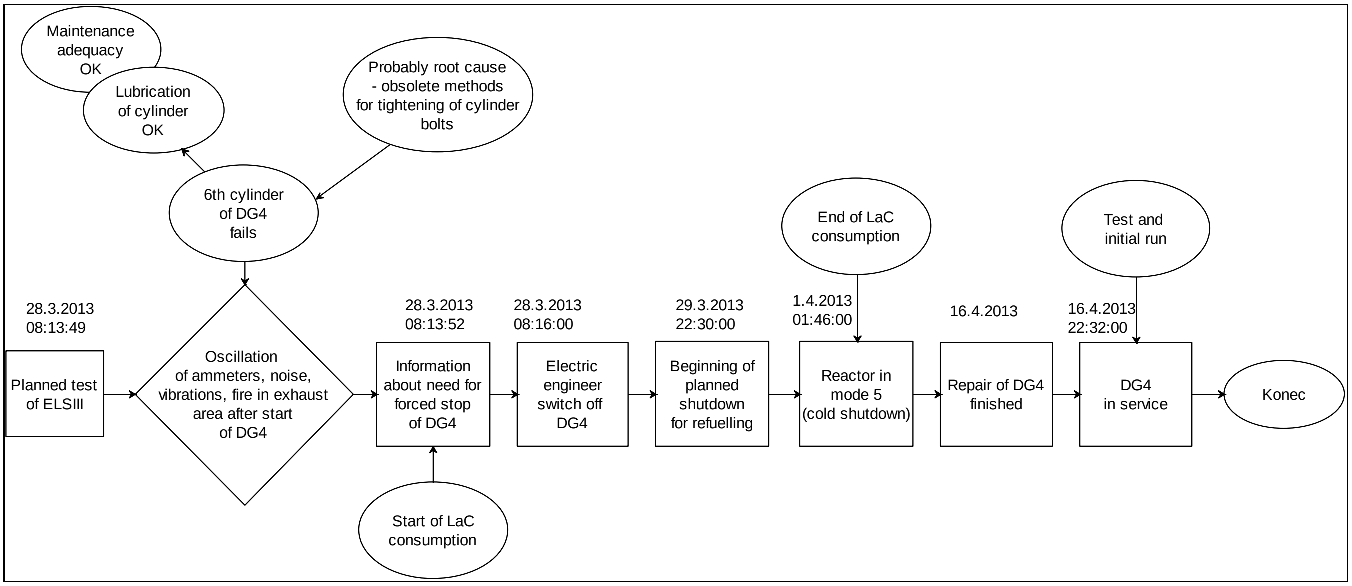

Fig. 3. The course of event

V.D. Results

For all relevant operational modes (represented by corresponding POSs) the Core Damage Frequency (CDF), Conditional Core Damage Frequency (CCDF) and Incremental Conditional Core Damage Probability (ICCDP) values were calculated by PSA model. The PSA model logic was set in accordance with analyzed event. The basic value of CDF is 4.67E-06/year and the calculated value of CCDF is 4.91E-06/year for power operation. Thus ΔCDF is 2.00E-07/year and ICCDP is 1.30E-09. Based on the value of the ΔCDF the event could by rated as Safety significant event (see Table I), but the value of ICCDP is lower than threshold for this risk event level category. The final result is that **the event is non safety significant event during operation at power**.

Similar calculations were carried out also for other relevant modes during shutdown. In mode 3 (hot standby $T_{primary\ circuit}$ >180°C) the value of ΔCDF is 1.40E-06/year (higher than threshold for ASP category), but due to relatively low value of ICCDP (2.89E-09) the event is non safety significant in mode 3. In cases of mode 4 (steam-water phase with auxiliary feed water pumps in operation, $T_{primary\ circuit}$ >180°C) and mode 5 (pressure in primary circuit > 2MPa and temperature of primary circuit is under the temperature of brittle fracture) the results are similar as in mode 1. The values of ΔCDF are in range for safety significant event but the value of ICCDP is in lower range. The final result is that **the event is non safety significant event in low power and shutdown states.**

V.D.1What if analysis

Within "What if" analysis we examined two possibilities that could arise when an event occurs in other circumstances. In a real situation the fault of DG4 occurred shortly before the planned shutdown for refueling. It was fortunate for the operator, because it had not to forcibly shut down of the unit due to the requirements of Limits and Conditions (DG must be put into operational condition within 72 hours - the actual repair took more than 19 days). In this step of "What if" analysis, we assumed that the hidden fault on DG occurred at the beginning of the operation on the power after the shutdown and operability tests of DG would fail to detect the fault. This corresponds to a finding a minimum period of unavailability of DG, after which the event will have a risk level of safety significant event or even ASP. The result for this case is shown in the graph in Figure 4.

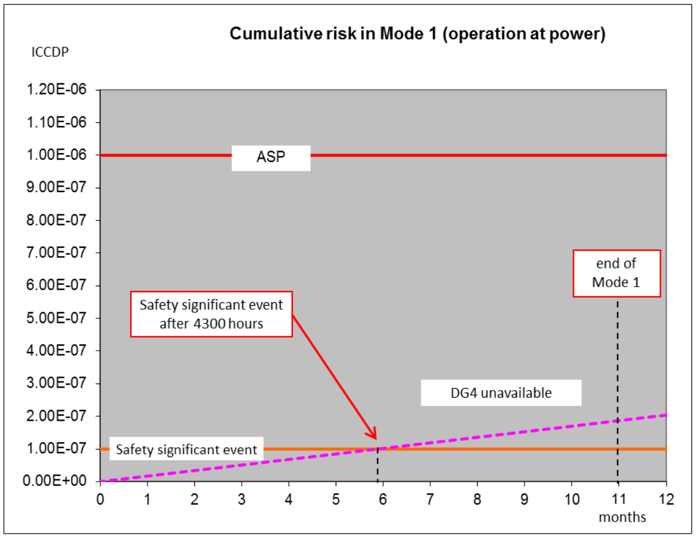

Fig. 4. The course of event

The graph shows that the event would become Safety Significant Event after about 4300 hours. This corresponds to the case that two or three tests of DG of DG availability would be ineffective (test of DG availability is performed every two months).

The second case was focused on the evaluation of possible common cause failure. During subsequent inspections after the failure the significant degradation was not found in other cylinders of DG4, however the root cause was not clearly demonstrated. One potential contributor was obsolete scheme of bolts tightening (in a few cases loosen or overtightened bolts were found, which may deform the cylinder liner and cause its fracture).

As the most conservative case the simultaneous outage of two DGs (out of three) caused by the same mechanism was considered. The calculated value of CCDF is 7.17E-06/year for operation at power. The ΔCDF is 2.50E-06/year and ICCDP is 1.60E-08. Based on the value of the ΔCDF the event could by rated as ASP (see Table I), but the value of ICCDP is lower than threshold for Safety Significant Event category. The final result is that in case of simultaneous failure of two DG **the event is non safety significant event during operation at power**.

VI. CONCLUSIONS

PSA applications are an important tool for a significant extending of the operational risk assessment at NPPs. As a complement to the deterministic analysis it is used to quantify the significance of the operational risk from different perspectives. Based on detailed probabilistic model the precursor analysis enables to assess the risk level of operational events, including scenarios that may not be obvious at first glance and can be overlooked in the context of the traditional approach.

This article presents the approach to precursor analysis in the Czech Republic on the basis of our own methodological process by using the PSA model, which includes all necessary aspects for the successful implementation of this analysis. Positively sets cooperation with the OEF staff on both Czech NPPs creates the necessary basis for the utilization of ASP analyzes.

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