INSIGHTS FROM COMPARISON OF TURBINE HALL FIRE RISK EVALUATED BY THE SIMPLIFIED AND DETAILED APPROACHES

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The goal of this study is to compare turbine hall fire risks evaluated by the simplified and detailed approaches. In fire PSAs performed for nuclear power plants worldwide, the detailed fire analysis of complex compartments is a laborious process, therefore a simplified fire modeling approaches are usually used. The turbine hall is a typical complex fire compartment with large variety of equipment and combustible materials scattered in the compartment. The simplified fire modeling usually implies simultaneous fire-induced failures in turbine hall that could lead to significant core damage risk contribution even though the majority of systems located in turbine hall are non-safety systems. Therefore, the comparison of application of detailed approach for turbine hall risk evaluation could be reasonable. This paper presents comparison of turbine hall fire risk evaluations by the simplified and detailed approaches and insights related to applicability of those approaches.

I. INTRODUCTION

Fire risk profile of Nuclear Power Plant is in general unique and depends on numerous factors such as design, plant procedures, organization of fire safety issues and others. Observation of risk profiles for VVER plants shows that Turbine Hall fires are usually one of the main contributors in Fire PSAs (see Figure 1[1]).

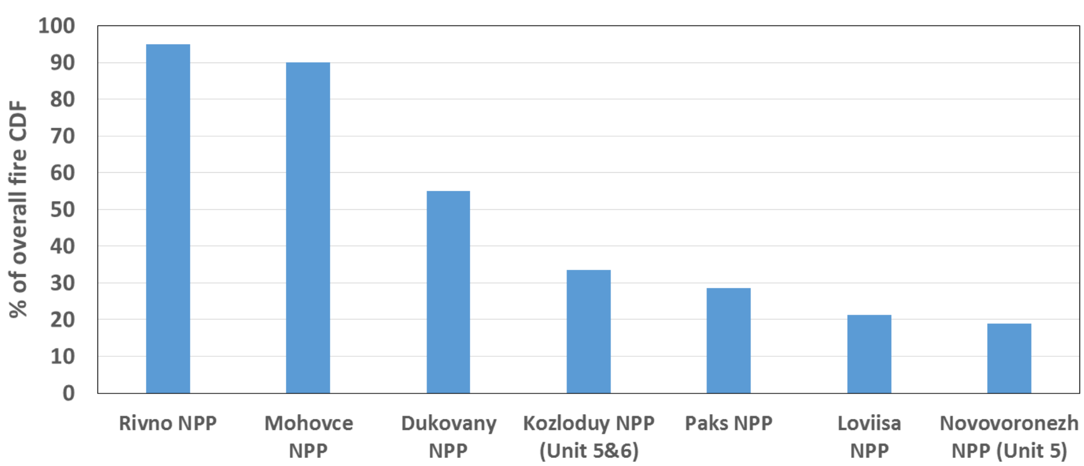

Fig. 1. Contribution of fires in Turbine Hall to overall fire CDF for different VVER reactors.

Since 2002 Fire PSA study for Armenian NPP Unit 2 (ANPP) evolved through different versions of PSA model. During those years one of the non-negligible fire risk contributors were scenarios with fire in Turbine Hall. Though those fire scenarios are hidden by other design specific fire issues (confinement fires and fires in mezzanine) [1,2], the risk coming

[1] The information about VVERs were taken from different sources dated within last decade, therefore it could happen that some of the data don't fully correspond to the current risk profiles. However presented values enable to understand level of impact coming from fire in TH.

from turbine hall fires could not be considered as negligible for Armenian NPP Unit 2 (different values for different fire PSA versions – up to 10%), detailed risk insights from fires are presented in [1,2].

The first versions of fire PSA for Armenian NPP Unit 2 (ANPP) were using simplified approach for Turbine Hall modeling. The simplified approach implied conservative assumptions of loss of all equipment in Turbine Hall, which was typically leading to scenarios with loss of main and auxiliary feedwater systems. Available design provisions allow to mitigate above mentioned scenarios by implementation one of the following procedures:

- Water supply to SG using seismically protected emergency feedwater system and steam relief from secondary side using steam generator safety valves
- Water supply to SG using diesel-driven pump and steam relief from secondary side using steam generator safety valves
- Primary feed and bleed procedure

Above-mentioned mitigation functions lead to significant decrease of CDF coming from Turbine Hall fire scenarios. However, during regular update of fire PSA model, the thorough investigation of the cable routings and additional walkdowns allowed PSA analysts to reveal new failure modes and possible safety challenges in case of fires in Turbine Hall. Particularly besides loss of main and auxiliary feedwater systems, it was found necessary to consider following failure modes and scenarios:

- spurious opening of steam relief valves or failure to close TG stop valves and simultaneous failure to close certain fast steam isolation valves
- failure of switchgear equipment due to the heat transfer to adjacent compartments in case of large fires in Turbine Hall

Newly revealed failure modes were found to be potentially significant from the point of view of risk profile. Rough estimation lead to the conclusion that application of simplified approach with conservative assumptions could seriously distort the risk profile and create obstacles for further risk informed decision making. Therefore, it was decided to implement detailed analysis of fires in Turbine Hall in order to obtain realistic risk profile.

This paper presents comparison of the results of turbine hall fire risk analysis by the simplified and detailed approaches and insights related to applicability of those approaches.

II. TURBINE HALL DESCRIPTION

The Turbine Hall of Armenian NPP Unit 2 is a typical building of VVER-440/230 reactors with twin units. The turbine hall layout with indication of Fire PSA locations and adjacent premises is shown in Figure 2.

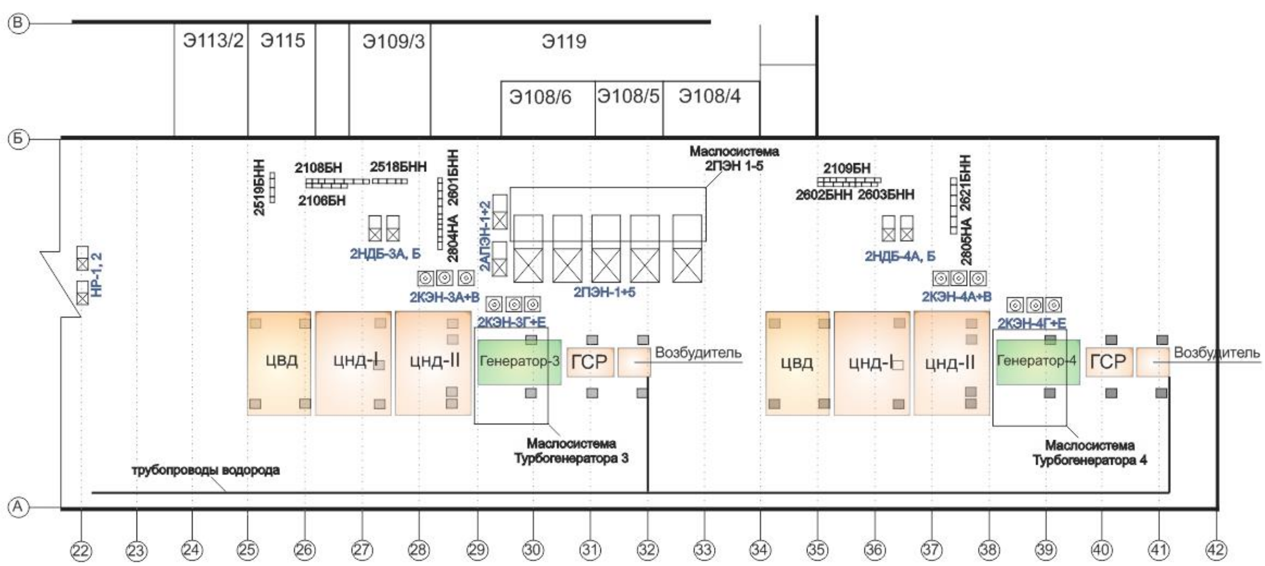

Fig. 2. The layout of Turbine Hall of Armenian NPP Unit 2 (elevations -3.6 and 0.0)

The turbine hall of Armenian NPP is rectangular building with length of 253m and width of 36m, height of the TH is 25.5m (-3.8m to 21.5m elevation). Four turbine generators are located in the turbine hall: TG-1, 2 of the ANPP Unit 1 (not operating) and TG – 3, 4 of the ANPP Unit 2.

In the current investigation, the focus was made on Unit 2 related equipment: TG – 3, 4 and corresponding systems and components related to safety of Unit 2 (see Figure 1). The list of the equipment located in Turbine Hall and considered in fire PSA is presented in Table 1.

TABLE I. Turbine hall equipment modeled in PSA

Elevation	Equipment code	Description	Temperate resistance limit
▼-3.6 ÷▼+14.7	Cables	Numerous cables of Turbine Hall equipment (both power and control cables)	~330 ºC
▼-3.6	2NDB-3,4A,B	Drainage tank pumps	120ºC
▼-1.8	2APEN-1,2	Auxilliary feedwater pumps	140 ºC
▼-1.8	2PEN-1÷5	Main feedwater pumps	120 ºC
▼0.0	2804NA	AC cabinet to supply FSIVs - fast steam isolation valves (1st channel), Steam dump valve to the atmosphere (BRUA-3) and feddwater line valves (24VP-9)	65 ºC
▼0.0	2805NA	AC cabinet to supply FSIVs - fast steam isolation valves (2nd channel), Steam dump valve to the atmosphere (BRUA-4)	65 ºC
▼0.0	2518BNN	AC cabinet to supply SG level control valves (ARU SG-1÷3, RU SG-2) and feedwater line valves (21VP-10, 22VP-10 valves)	65 ºC
▼0.0	2106BN	AC cabinet to supply feedwater line valve (26VP-10)	65 ºC
▼0.0	2108BNN	AC cabinet to supply SG level control valve (RU 2SG- 1)	65 ºC
▼0.0	2519BNN	AC cabinet to supply feedwater line valves (22VP-9, 26VP-9) and SG level control valve (RU 2SG-5)	65 ºC
▼0.0	2602BNN	AC cabinet to supply SG level control valve (RU 2SG-6) and feedwater line valves (24VP-10, 25VP-10)	65 ºC
▼0.0	2603BNN	AC cabinet to supply SG level control valve (RU 2SG- 4)	65 ºC
▼0.0	2624BNN	AC cabinet to supply feedwater line valves (21VP-9, 23VP-9)	65 ºC
▼0.0	2601BNN	AC cabinet to supply Steam dump valves to the condensers (BRU-K-3,4, 25VP-9)	65 ºC
▼0.0	2109BN	AC cabinet to supply SG level control valve (RU 2SG-3) and feedwater line valve (23VP-10)	65 ºC
▼0.0	NR-1,2	Residual heat removal (RHR) pumps	120 ºC
▼+6.3	BRU-K TG-3,4	Steam dump valves to the condenser	140ºC
▼+9.6	SK TG-3,4	Turbines' stop valves	140ºC
▼+14.7	RU SG-1-6	SG level control valves	140ºC
▼+14.7	ARU SG-1-6	SG level emergency control valves	70 ºC
▼+14.7	BZOK-1-7	Fast steam isolation valves	100 ºC
▼+14.7	SG SV-1-12	SG safety valves	100 ºC
▼+14.7	BRU-A TG-3,4	Steam dump valves to the atmosphere	70 ºC
▼+14.7	RUR-1,2	Steam dump valve to the RHR cooling heat exchangers	70 ºC
▼+14.7	21÷26VP-9	Valves on the feedwater lines to SG	70 ºC
▼+14.7	21÷26VP-10	Valves on the feedwater lines to SG	70 ºC

III. METHODOLOGY AND OBTAINED RESULTS

The impact of the fire on the above-mentioned equipment (see Table 1) have been analyzed using 2 different approaches: detailed approach and simplified approach chapters. In the detailed analysis of the defined scenarios, the location and amount of combustible materials were taken into account, whereas simplified approach implies failure of all of the equipment mentioned in Table 1 in worst failure modes from the core damage point of view.

III.A. Detailed approach for Turbine Hall fire risk analysis

The detailed approach for Turbine Hall fire risk analysis was taken from NUREG/CR-6850 [3] and it's Supplement document [4]. According to the methodology described in NUREG/CR-6850 and it's supplement the following ignition sources and corresponding fire scenarios were considered in Turbine Hall:

- Excitor
- TG oil system
- Main feedwater oil system
- TG hydrogen
- Cable fire
- Catastrophic fire scenario (including all major fire sources)

The assumptions and details of the analysis for each ignition source is presented in sections III.A.1÷6. The obtained results are summarized in section III.C.

III.A.1. Generator excitor fire

Excitor is a separate device, which is located on the TG deck. According to the methodology presented in NUREG/CR-6850 [3] the fire can be assumed to be localized to the excitor area. It is assumed that the fire damages only the excitor itself, hence the consequences of this fire scenarios are limited to the unavailability of associated TG.

III.A.2. Fire on TG oil system

According to the methodology described in NUREG/CR-6850 two severity levels of oil fire scenarios were considered: Limited fire on TG oil system and Severe fire on TG oil system.

Limited fire on TG oil system. For limited oil fires, the methodology described in NUREG/CR-6850 recommends to assume that fire could only damage equipment located in the proximity of the turbine generator and the turbine generator oil system piping. After detailed walkdowns in the turbine hall it was assumed that in case of the limited hydrogen fire the consequences are limited to the failure of corresponding TG.

Severe fire on TG oil system. The detailed analysis was performed for TG severe oil fires to identify the dynamics of Fire PSA equipment failures. In the current scenario, the oil leakage from the TG oil system was considered to form a pool with diameter of 1,54m, it has been assumed that the spilled oil ignites instantly on the entire area of the pool (the oil pool fire power is 4 MW, the duration 7200 sec). It has been assumed that if the fire is not extinguished in 7200 sec, the fire scenario turns in to the catastrophic fire scenario, which is described in section III.A.3. The location of oil spill and fire selected conservatively taking into account location of target equipment.

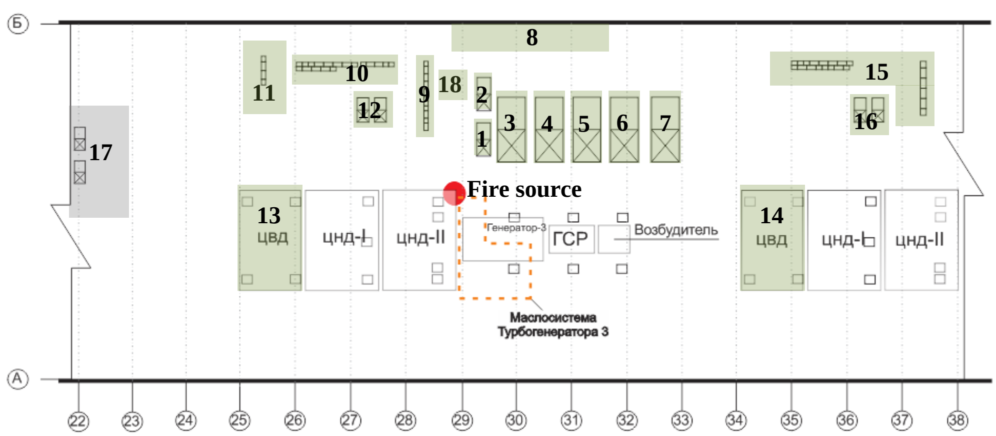

Fig. 3. Location of fire source and target equipment groups for severe fire scenario on TG oil system

III.A.3. Hydrogen fire

According to the methodology described in NUREG/CR-6850 two severity levels of hydrogen fire scenarios were considered: Limited and Severe hydrogen fire.

Limited hydrogen fire. For limited hydrogen fires, according to the methodology, there is no need in a deterministic detailed analysis. The methodology described in NUREG/CR-6850 recommends to assume that fire damages equipment which are located in the proximity of the turbine generator and the hydrogen pipe line. After detailed walkdowns in the turbine hall it was assumed that in case of the limited hydrogen fire the consequences are limited to the failure of corresponding TG.

Severe hydrogen fire. Severe hydrogen fire can damage the equipment located in the range of the visibility from the fire (NUREG/CR-6850). Taking into account the worst possible location of severe hydrogen fire, the failure of the following equipment was postulated:

- Electrical motors APEN-1,2
- Electrical motors PEN -1÷5,
- Electrical cabinet 2804NA,
- Electrical cabinet 2601BNN,
- TG stop valves on TG -3,4

III.A.4. Main feedwater oil system fire

According to the methodology described in NUREG/CR-6850 Supplement 1 [4] three severity levels of Main feedwater (MFW) oil system fire scenarios were considered: very large oil fire, large oil fire and small oil fire.

Very large fire on MFW oil system. For this scenario the Supplement 1 of NUREG/CR-6850 [4] recommends to consider a 100% oil spill from the oil system in the scenario. The oil system of ANPP MFW was assumed to form the oil pool with the diameter equals to 1,54m, the power of oil pool fire is 4 MW, the duration of fire was taken 4193 sec which was calculated based on the methodology presented in NUREG -1805 [5]. The fire source and target equipment groups are presented in Figure 4. Oil spill was postulated in the worst place in terms of damage to the PSA equipment (see. Fig. 4).

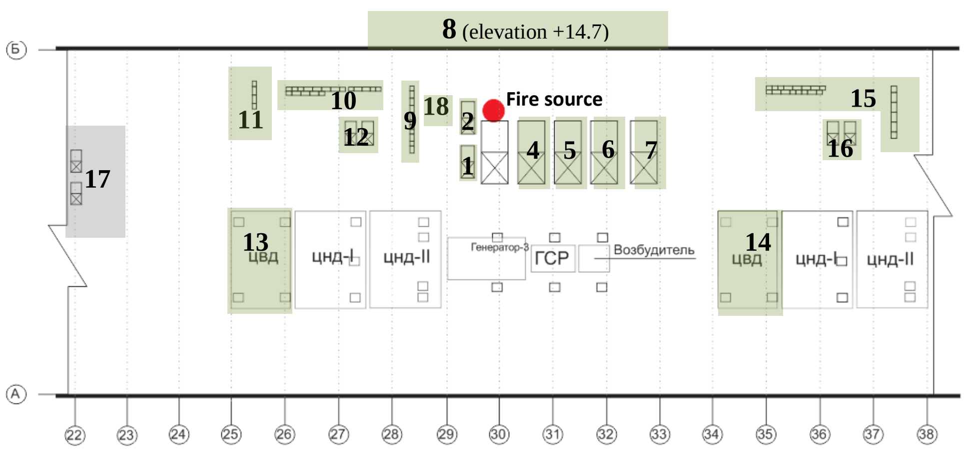

Fig. 4. Location of fire source and target equipment groups for fire scenarios on MFW oil system

Large fire on MFW oil system. For this scenario the Supplement 1 of NUREG/CR-6850 [4] recommends to consider a 10% oil spill from the oil system in the scenario. This scenario differs from the previous scenario only by amount of spilled oil. Taking into account that boundary and initial conditions remain the same as in the previous scenario, the results of the previous detailed analysis can be used to identify time windows for the PSA equipment failure.

Small fire on MFW oil system. For this scenario according to the used methodology [4], there is no need in a deterministic detailed analysis. The methodology described in NUREG/CR-6850 supplement 1 [4] recommends to assume that fire could damage equipment which is located in the proximity of the fire source. The walkdown showed that only the feed water pump, which is selected as a fire source could be assumed as failed, no other equipment are expected to be damaged in case of small fire on MFW oil system.

III.A.5. Cable fire

As it was identified during the walkdown and analysis of the cable tracing, the majority of cables of PSA equipment are routed through the vertical cable shafts 7A, 8A, 9A and 10A located at the inner wall of Turbine Building crossing elevations 0.0 to +14.7 (see Figure 5).

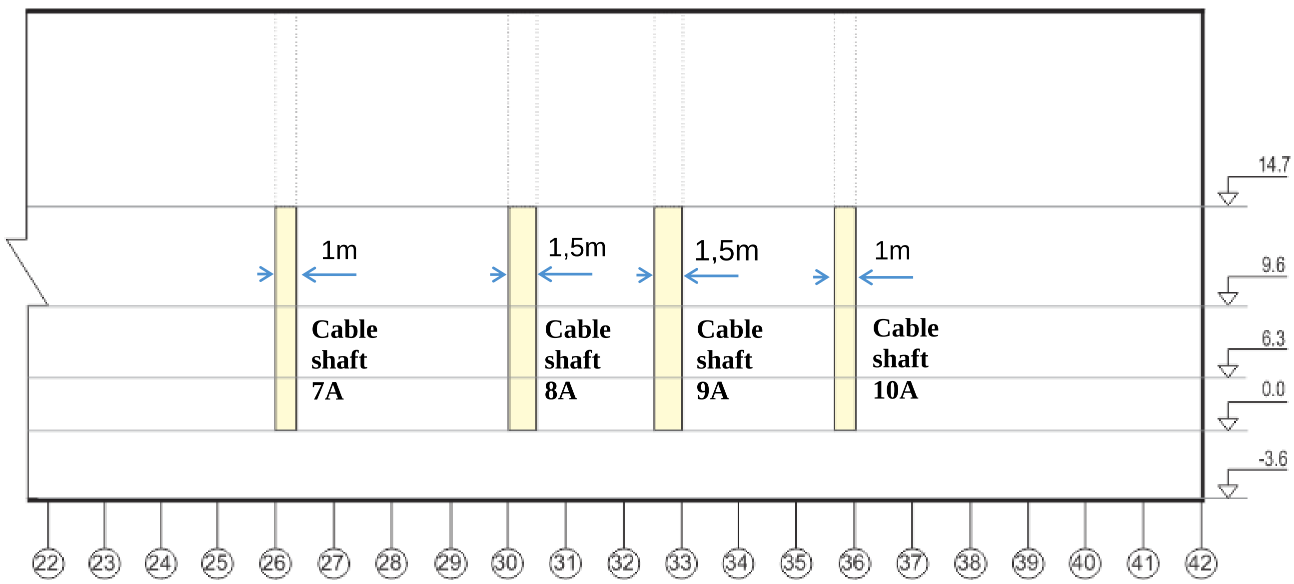

Fig. 5. Location of cable shaft taken into account in TH cable fire scenarios

Therefore cable fire scenarios were limited to the consideration of overall 4 cable fire scenarios, reflecting fires in above mentioned cable shafts. It was conservatively assumed that all the cables located in corresponding cable shaft will be damaged in case of fire. Cables postulated to fail in worst possible failure mode from the point of view of core damage.

III.A.6. Catastrophic fire

Based on the methodology described in NUREG/CR-6850 the catastrophic fire scenario implies failure of the all safety-related equipment in Turbine Hall. Therefore, the equipment listed in Table 1 was postulated as failed in case of the catastrophic fire.

However, in addition to NUREG/CR-6850 methodology the another safety challenge has been considered: the question has been raised related to the possible heat transfer from Turbine Hall to adjacent compartments in case of large power of fire in case of catastrophic fire scenario. The duration of fire scenario was chosen such that the catastrophic fire scenario frequency would equal 10^{-7}[1/y] (taking into account probability of failure to suppress the fire). Numerical Results for Suppression Curves (NUREG/CR-6850 appendix P) were applied to determine the duration fire scenario and failure probability to suppress the fire [3]. As a result, the estimated duration for catastrophic fire was estimated as 21360 sec.In this scenario two types of combustibles were considered: cable isolation (PVC) and TG oil. It was assumed that total amount of oil available in Turbine Hall is included in fire scenario. All combustibles were conservatively accounted in the one fire source shown in the Figure 6.

The Turbine Hall is connected by wall to intermediate building where switchgear compartments are located. Failure of equipment in switchgear compartments could lead to a significant challenge to safety of power plant in terms of the station blackout. Location of switchgear compartment is shown in Figure 6. The compartment were considered as a target for heat transfer with a electrical equipment damage criteria postulated as $65^{O}C$ [3].

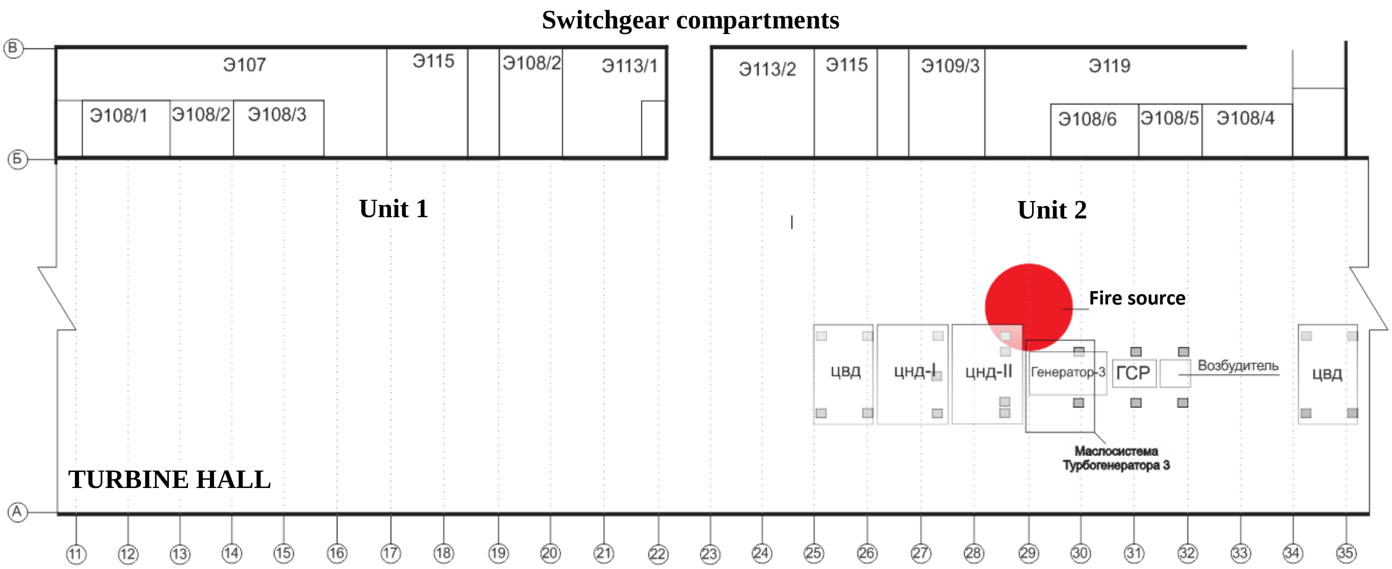

Fig. 6. Location of fire source and switchgear rooms considered as the target for heat transfer

The analysis of heat transfer fro Turbine Hall to the switchgear compartments was modeled using COCOSYS (Containment Code System) code developed by GRS (Germany). COCOSYS allows to comprehensively simulate appropriate processes and evaluate temperature behavior in time in the adjacent compartments. For the turbine hall and adjacent compartment analysis 128 control volumes were modeled which are interconnected using 262 junctions. The walls that are made of 25 cm thick cinder blocks are modeled using 45 heat structures. The computational model of the turbine hall and adjacent compartments is presented in Figure 7.

Fig. 7. COCOSYS computational model of the turbine hall and adjacent compartments

To take into account temperature distribution along height of the turbine building it was virtually subdivided in two “storeys”. The following initial conditions are taken into account:

- Temperature in the turbine hall and in the environment: 40°C
- Temperature in DC battery compartments: 35°C (The maximal allowable temperatures in the switchgear compartments according to technical specifications)
- Temperature in switchgear compartment: 40°C (The maximal allowable temperatures in the switchgear compartments according to technical specifications)
- Pressure in all compartments and the environment: 100 kPa
- Ventilation systems availability was not considered.`
- The initial atmosphere is defined as consisting of nitrogen and oxygen according to natural composition (79 to 21 vol.%).

The results of the calculations performed by COCOSYS computational model are presented in the Figure 8.

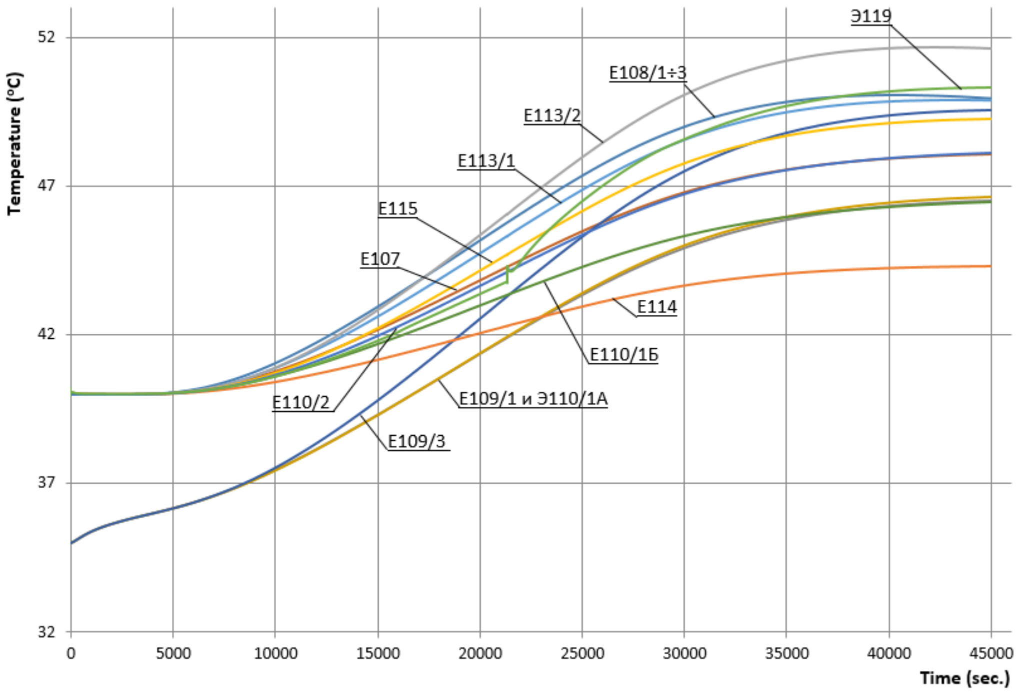

Fig. 8. Temperature behavior in compartments adjacent to Turbine Hall

Taking into account that the criteria for damage temperature of equipment in the adjacent compartments is 65°C [3], it can be stated that even in case of the catastrophic fire scenario in the turbine hall the damage criteria of equipment in adjacent compartments is not violated. Therefore, the heat transfer from TH fires to adjacent compartments could be neglected.

III.B. Simplified approach for Turbine Hall fire risk analysis

The simplified approach implies failure of all equipment in Turbine Hall and therefore the consequences of it is similar to the catastrophic fire scenarios described in III.A.6. The only difference is the frequency of that scenario which is in this case taken as equal to the fire ignition frequency in Turbine Hall (8.43E-02 [1/y]).

III.C. Summary results

The results of analysis presented in sections III.A and III.B allowed PSA analysts to outline scenarios for incorporation in the PSA model. Scenarios were developed both for detailed and simplified approaches. The list of scenarios are summarized in Table 2.

TABLE II. List of fire scenarios for Turbine Hall

Fire scenarios	Conditional probability	Damaged equipment	Time to failure (sec.)
Application of the detailed approach			
Excitor fire	3.75E-02	Generator excitor	0
Limited fire on TG oil system	1.31E-01	One of the turbines	0
Severe fire on TG oil system	6.88E-03	Electrical motors 2NDB-3A,B	670
		Electrical cabinets 2804NA, 2601BNN	6640
		Electrical cabinets 2518BNN, 2624BNN	7120
Limited hydrogen fire	5.71E-02	One of the turbines	
Severe hydrogen fire	1.17E-02	Electrical motors APEN-1,2, PEN -1÷5, Electrical cabinets 2804NA, 2601BNN, TG stop valves on TG -3,4	0

Very large fire on MFW oil system	1.13E-03	Electrical motors PEN -1	0
		Electrical motors APEN-2	850
Large fire on MFW oil system	1.02E-02	Electrical motors PEN -1	0
Small fire on MFW oil system	3.22E-01	Electrical motors PEN -1	0
Fire in cable shaft #7A	8.34E-02	All cables in cable shaft 7A (Failure of BRU-K valves, partial failures of auxiliary and main feedwater systems, loss of NDB-4A,B, failure of 1st channel of essential service water system, failure of RHR)	0
Fire in cable shaft #8A	1.25E-01	All cables in cable shaft 8A (Failure of MFW oil system, Failure of FSIVs (1st channel), failure of primary circuit injection pumps control (2nd channel), loss of NDB-3A,B)	0
Fire in cable shaft #9A	1.25E-01	All cables in cable shaft 9A (Partial failures of auxiliary and main feedwater systems, Partial failure of main condensate system, Failure of spray system's control)	0
Fire in cable shaft #10A	8.34E-02	All cables in cable shaft 8A (Failure of FSIVs (2nd channel), failures in emergency power supply for RHR, 1,2APEN, NDB-3B pumps)	0
Catastrophic fire scenario	6.25E-03	All equipment in turbine hall	0[2]
Application of the simplified approach			
Catastrophic fire scenario	1.00E+00	All equipment in turbine hall	0

The conditional probability of fires were calculated based on parameters, which are presented in the table O-1 in appendix O of NUREG/CR-6850 [3], as well as on the available statistical data from Armenian NPP and other VVER NPPs [6]. VVER specific fire statistical data were mainly used to tune conditional probabilities for different fire scenarios. Final list of fire scenarios and distribution of their conditional probabilities are shown in Figure 9.

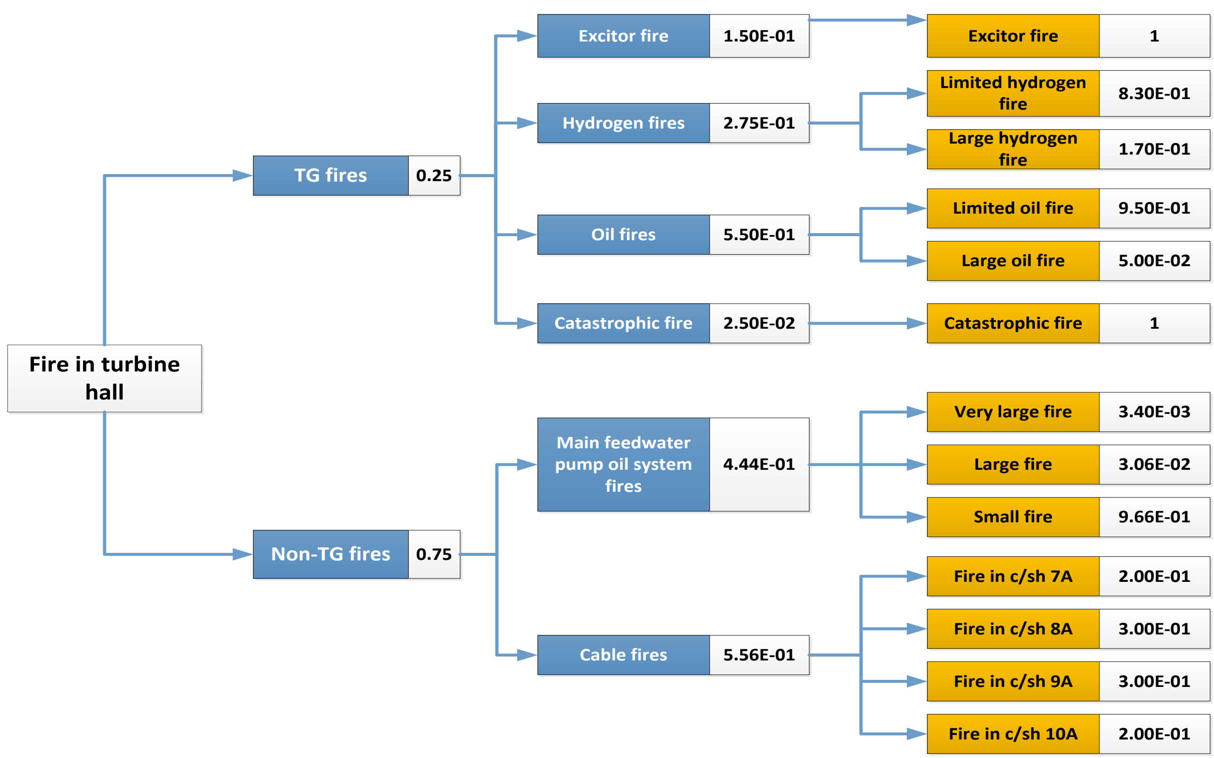

Fig. 9. Conditional probabilities of developed fire scenarios for turbine hall in case of application detailed fire risk analysis approach

[2] Fire control possibilities were taken into account in the calculation of conditional probability of catastrophic fire

IV. CDF CALCULATION RESULTS

Performed calculations allowed identifying the fire behavior in the turbine hall and estimating time window available for operator before the failure of safety-related equipment. The fire scenarios presented in Table II have been incorporated in the plant specific PSA model of Armenian NPP Unit 2.

Quantifications have been performed separately using results of application of detailed and simplified approaches. Quantification shows that mean value of core damage frequency is 9.34E-06 [1/y] for detailed analysis and 1.22E-05 [1/y] for simplified analysis (31% increase) (see Figure 10). The contribution of Turbine Hall fires in overall CDF changed from 5.79E-07 [1/y] to 3.44E-06 [1/y] (increase almost by factor of 6).

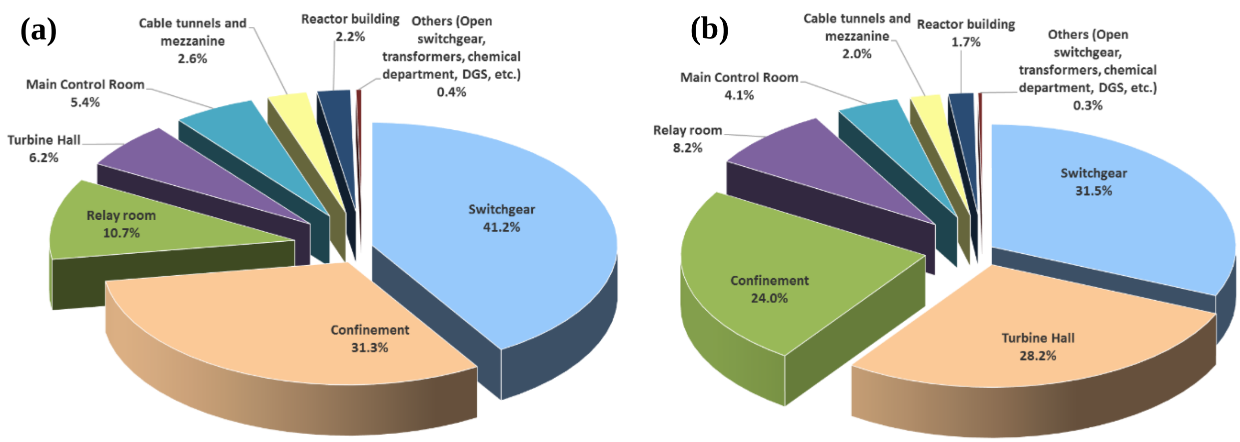

Fig. 10. Fire risk profile in case (a) – detailed analysis of Turbine Hall fire, (b) – simplified analysis of Turbine Hall fire

Importance analysis also shows that some of the components obtain overestimated importance factors (e.g. Fussel-Vessely) in case of simplified modeling of Turbine Hall fire scenarios. Particularly following equipment become much more important (one to two order of magnitude higher Fussel-Vessely importance factor) than in case of detailed modeling of Turbine Hall:

- Electrical cabinets 2804NA and 2805NA
- Fast steam isolation valves
- Steam dump valves (BRUK and BRUA)

Increased importance of above mentioned equipment is conditioned by increased importance of scenarios with possibility of rapid overcooling and/or failures of steam dump valves due to the fire in Turbine Hall.

V. CONCLUSIONS

Since 2002 Fire PSA study for Armenian NPP Unit 2 (ANPP) evolved through different versions of PSA model. The simplified approach for Turbine Hall modeling has been utilized in the first versions of fire PSA. The simplified approach was found to be questionable and potentially overconservative taking into account all possible fire-induced failure modes. Therefore, it was decided to implement detailed analysis of fires in Turbine Hall in order to obtain realistic risk profile. The comparison of the results of turbine hall fire risk analysis performed by the simplified and detailed approaches was presented in this paper.

Results presented in section IV allow PSA analysts to come up with the conclusion that simplified modeling of fire in Turbine Hall is leading to the overconservative results and to the significant distortion of plant risk profile. Thus, it was demonstrated that simplified modeling of fire in Turbine Hall could lead to the inadequate platform for further risk-informed decision making. Therefore, it is recommended to apply detailed methodology for Turbine Hall fire risk analysis. In addition, the necessity to reveal and address all possible fire induced failure modes was highlighted (e.g. cable fire induced spurious activation of steam dump valves, simultaneous failure to close of TG stop valves and failure to close steam isolation valves).

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