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HEPs Calculation for FLEX Strategies in Response to APR1400 Extended SBO for Risk-Informed Decision Making

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1. Introduction

One of the representative accidents related to the electric power in nuclear power plants (NPPs) is Station Blackout (SBO). Station blackout means loss of offsite power (LOOP) concurrent with turbine trip and unavailability of the onsite emergency alternating current (ac) power system but it does not include the loss of available ac power to buses fed by station batteries through inverters or by alternate ac (AAC) sources [1]. The Fukushima nuclear power plant (NPP) accident in 2011 showed that SBO for several days, the so-called extended SBO, had a huge impact to increase the core heat and fuel damage. Based on the state of the art reactor consequence analyses (SOARCA) report, the extended SBO is considered to be among the main contributors to core damage frequency [2]. Since that accident, nuclear industries developed onsite and offsite equipment concept that provides an additional layer of defense in depth, called diverse and flexible mitigation strategies (FLEX). The most compelling evidence is the U.S. Nuclear Energy Institute (NEI) developed several FLEX implementation guides for beyond design basis scenarios to address extended SBO and loss of the ultimate heat sink (LUHS) [3, 4].

This paper is a continuation of the previous work entitled "Comparative Study of FLEX Strategies for Extended Station Blackout (SBO) using PRA" [5] by considering a large mobile gas turbine generator (GTG), a small GTG and a primary FLEX pump. The accident sequences development of former work in response to extended SBO for APR1400 was up to the mark. In contrast, the human error probabilities (HEPs) were calculated according to the NEI 16-06 guide [4] and it needs to refine. This is because NEI guide has been developed considering U.S. NPPs operating experiences but every country has diverse nuclear infrastructure status as well as distinct reactor design. Thereupon, HEPs calculation should be based on the country-specific scenario. It is also evident that human contribution clearly dominates the risks to modern technological systems. In this paper, we recalculated HEPs for APR1400 extended SBO using cause-based decision tree (CBDT) and technique for human error rate prediction (THERP) methods and compared the results with the previous work [5] as well as NEI 16-06 guide [4]. The paper does not discuss dependency analysis of multiple human failure events as FLEX procedures are still in the development stage.

2. Development of Accident Sequences for APR1400 Extended SBO

This section describes accident sequence development to cope with an APR1400 extended SBO scenario which is graphically modeled in event tree. In the APR1400, extended SBO involves complete loss of ac electric power to the Class 1E and non-Class 1E switchgear buses as well as the failure of a non-Class 1E AAC GTG [6]. Under the extended SBO condition, the only dc battery is available for the turbine driven auxiliary feedwater pump (TDAFWP) which supply cooling water to the steam generator (SG). The capacity of dc battery is 8 hours and within this period plant safety needs to be recovered. Henceforth, a small mobile GTG (1 MW) could be connected to the class 1E dc bus to recover dc power for maintaining secondary heat removal [5].

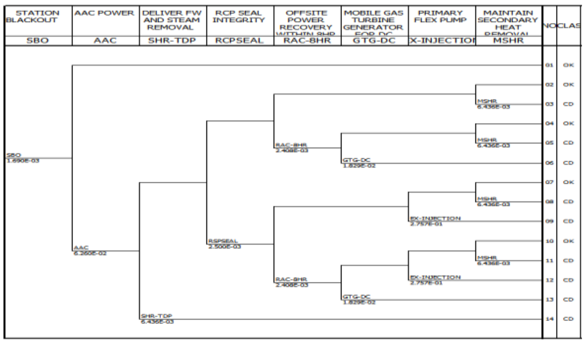

Fig. 1. Event Tree for an Extended SBO using Small GTG

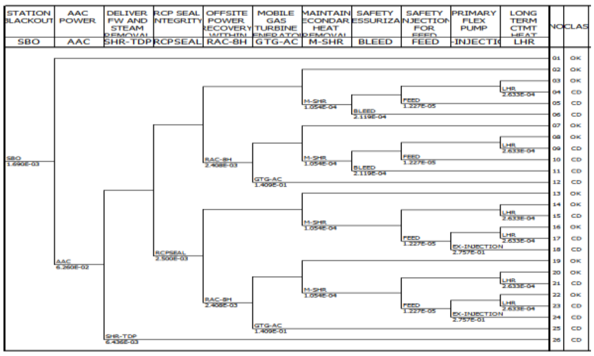

Fig. 2. Event Tree for an Extended SBO using Large GTG

On the other hand, a large mobile AAC GTG (3.2 MW) could be connected to one division of the 4.16 kV class 1E buses and the purpose is to recover ac power to maintain the secondary heat removal, feed and bleed operation and containment heat removal. In both cases, a primary FLEX pump is modeled to maintain reactor coolant pump (RCP) seal integrity. One primary FLEX pump could be connected to direct vessel injection (DVI) via the safety injection (SI pump) line to inject borated water into the core [5].

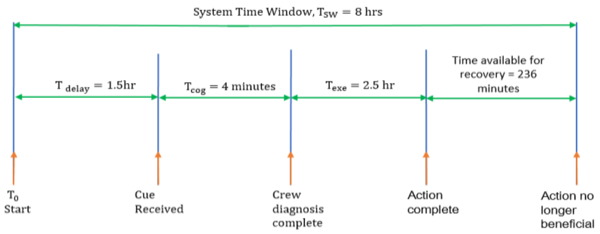

Fig. 3. Timing analysis for extended SBO

It is assumed that after 8 hours from the start of SBO, the mobile GTG is required or FLEX actions will not be successful. The brief time window analysis is stated underneath [4]:

Delay time, T_{delay} = 90 mins includes diagnose the situation and begin the deployment of the mitigating strategies equipment, measured from the time of SBO.
Cognition time, T_{cog} = 4 mins includes the time for operators to receive enough indication, evaluate the written instructions, and take any necessary preparatory actions to begin the deployment actions.
Execution time, T_{exe} = 150 mins which includes FLEX equipment transportation, installation, start and re-power the vital buses along with inclement weather.
Time available for cognition and recovery minutes T_w = 240 mins.

3. HEPs Calculation Using CBDT and THERP

In this paper, three post initiator human failure events namely operator fails to deploy and install a small GTG, a large GTG and primary FLEX pump under APR1400 extended SBO were studied to calculate HEPs using CBDT and THERP methods.

3.1 CBDTM

The cognition, P_{cog} without recovery and cognitive recovered, P_{CR} values were found 4.0×10^{-2} & 8.45×10^{-3} respectively. For each failure mechanism the endpoint branch had been chosen based on the following basis:

Table 1. Cognitive analysis for CBDTM

CBDTM Failure Mechanism	Branch	HEP
P_ca : Availability of information	**a**	**0.0**
Notes: Operator can access to all information and required indication to operate a plant in the main control room (MCR).		
P_cb : Failure of attention	**m**	**1.5×10^{-2}**
Notes: In general, within 2 hours from SBO initiation, the workload is assumed to be high. It may be necessary to monitor parameters and indicators continuously rather than one time check under SBO. It's is assumed that the indicator to be checked is always displayed on the front panel of the MCR because all of the controls in the modern control room are expected to be located in the front of the room. It is also predicted that operators concentrate on emergency operating guideline (EOG) and performs EOG-driven actions after the reactor trip. Thus, operators cannot wait for alarms to respond until the related parameter are mentioned in the EOG step.		
P_cc : Misread/ miscommunicate data	**a**	**0.0**
Notes: It is assumed that required indicator on the control board such as layout, demarcation, labelling, and others is always located easily. With the advanced digital I&C interface in the MCR, the indication is assumed to be "good". It also is predicted that formal communications will always be used when the specified value is transferred between operators.		
P_cd : Information misleading	**b**	**3.0×10^{-3}**
Notes: All cues are not as stated for these HFEs and the EOG may provide contingency actions which are instructions on how to proceed.		
P_ce : Skip a step in procedure	**g**	**6.0×10^{-3}**
Notes: It's assumed that it's always transparent for operators to proceed with the relevant instruction or stand-alone numbered step on the EOGs. The operator is required to use an additional procedure in addition to the EOG, so "multiple" branch is selected for these HFEs. For this operator action, related procedure step is "not graphically distinct". The use of place keeping aids is always assumed to be used due to the nature of the computerized procedure system (CPS).		
P_cf : Misinterpret Instruction	**a**	**0.0**
Notes: It is generally assumed that the wording of the procedures will be standard, clear. The step presents all information required to identify the actions directed and their objects.		
P_cg : Misinterpret decision logic	**a**	**1.6×10^{-2}**
Notes: It is assumed that the APR1400 EOGs provide "NOT, AND, OR, BOTH AND & OR" logic. It is assumed that the operators are trained and practiced about specified scenario to perform.		
P_ch : Deliberate Violation	**a**	**0.0**
Notes: The operators are always assumed to believe in the adequacy of instruction presented.		
	Initial P_{cog} (without recovery)	**4.0×10^{-2}**

As listed in Table 2, we assumed that Shift Technical Adviser (STA) review is possible to recover failure of attention (P_cb), information misleading (P_cd) and misinterpret decision logic (P_cg). In addition, CPS provides the tools to prevent skip a step in the procedure (P_ce) and can be reviewed by the extra crew.
Time available for recovery is 236 minutes which belong to zero dependence (ZD) but the dependency factor (DF) was increased from zero dependence (ZD) to moderate dependence (MD). This is because MD is usually assessed between the shift technical advisor (STA) and the operators for tasks in which the STA is expected to interact with them. For complete independence, the factor is the HEP itself (Pce case). For an initial estimate, a value of 0.1 was used.

Table 2. Cognitive recovered, P_{CR}

	Branch	Initial HEP	Self Review	Extra Crew	STA Review	Shift Change	ERF Review	DF	Multiply By	Final Value
P_ca	a	0.0	NC	0.5	NC	X	X		1.0	0.0
P_cb	m	1.5×10^{-2}	0.1	NC	0.1	X	X	MD	0.16	2.4×10^{-3}
P_cc	a	0.0	NC	NC	0.1	X	X		1.0	0.0
P_cd	b	3.0×10^{-3}	NC	0.5	0.1	X	X	MD	0.15	4.5×10^{-4}
P_ce	g	6.0×10^{-3}	0.1	0.5	NC	X	X		0.5	3.0×10^{-3}
P_cf	a	0.0	NC	0.5	0.1	X	X		1.0	0.0
P_cg	a	1.6×10^{-2}	NC	0.5	0.1	X	X	MD	0.16	2.6×10^{-3}
P_ch	a	0.0	NC	0.1	0.1	X	X		1.0	0.0
Sum of recovered P_ca through Pch = Total of cognitive recovered P_{CR}										**8.45×10^{-3}**

Based on the aforementioned discussion, the conditional HEPs values for MD were calculated using failure equation $Pr[F_{"N"}|F_{"N-1"}] = (1+6N)/7$ which represent probabilities of failure on Task "N" given failure on the immediately preceding task, "N-1" for P_cb, P_cd and P_cg decision trees [7]. For P_ca, P_cc, P_cf & P_ch, we multiplied the initial HEPs by 1 as no recovery factors are identified [8].

3.2 THERP

The underneath procedures [9,5] provide instruction to operators on steps to recover ac, dc power as well as RCS inventory for the safe operation of the plant under extended SBO for APR1400.

Table 3. FLEX deployment & installation procedures

Steps	Procedures
Step 01	Diagnose the plant abnormal conditions and perform abnormal procedure guideline.
Step 02	Verify reactor trip occurrence and perform post trip actions.
Step 03	Check LOOP occurrence and perform emergency operating procedures
Step 04	If the operator fails to activate EDG, then declare an SBO
Step 05	Operator check AAC DG availability. If not available extended SBO is declared.
Step 06	Operator load sheds dc bus to preserve battery for vital instrumentation & control
Step 07	STA may instruct the operator to deploy and install FLEX equipment.
Step 08	FLEX equipment deployment route are reviewed.
Step 09	Deployment of small GTG and large GTG in front of the auxiliary building.
Step 10	Operator checks status of the circuit.
Step 11	Connect powerline to 480V for small GTG.
Step 12	Connect powerline to class 1E 4.16kV for large GTG.
Step 13	Perform pre-operational checking of large GTG.
Step 14	Energize mobile small GTG.
Step 15	Energize mobile large GTG.
Step 16	Check procedure if the vital bus is not restored
Step 17	Deployment and staging of primary FLEX pump.
Step 18	Connect primary FLEX pump to IRWST line
Step 19	Connect primary FLEX pump hose line to SI injection line via DVI.
Step 20	Perform pre-operational check for primary FLEX pump.
Step 21	Start primary FLEX pump.
Step 22	Check procedure if RCS inventory is not recovered.

Table 4. Execution Performance Shaping Factors

Execution performance shaping factors		
Environment	Lighting	Portable
	Heat/humidity	Hot/Humid
	Radiation	Green
	Atmosphere	Normal
Special Requirements	Tools	Required
	Parts	Required
	Clothing	Available
Complexity of response	Execution	Complex
Equipment Accessibility (Cognitive)	Main control room	Accessible
Equipment Accessibility (Execution)	Auxiliary Building	Accessible

The execution stress level was considered high and modifier 5 value was used [10].

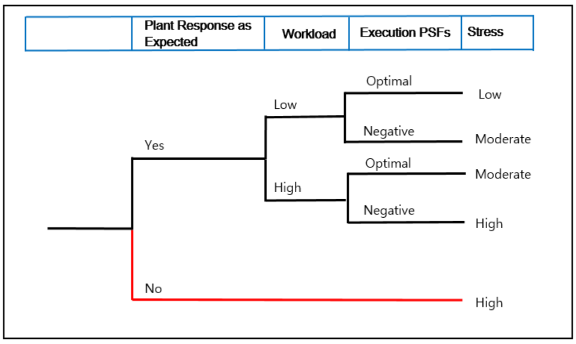

Fig. 4. THERP stress decision tree

All the critical steps error of omission (EOM) and error of commission (EOC) mean HEP values were taken from the EPRI HRA calculator manual [10]. The execution HEP without recovery (P_{exe}) and execution recovered (P_{ER}) calculations for a small portable GTG under APR1400 extended SBO are outlined in Table 5 and Table 6.

Table 5. P_{exe} without recovery for small mobile GTG

Procedure		Error type	THERP		HEP	Stress factor	Total Step HEP
Step No.	Action		Table	Item			
09	Deployment of small GTG in front of auxiliary building.	EOM	20-7b	1	4.17×10^{-4}	High	8.59×10^{-3}
		EOC	20-13	1	1.3×10^{-3}	High	
10	Operator checks status of circuit.	EOM	20-7	2	3.75×10^{-3}	High	2.53×10^{-2}
		EOC	20-10	6	1.3×10^{-3}	High	
11	Connect powerline to 480V for small GTG.	EOM	20-7b	2	1.25×10^{-3}	High	7.13×10^{-2}
		EOC	20-12	13	1.30×10^{-2}	High	
14	Energize mobile small GTG.	EOM	20-7b	2	1.25×10^{-3}	High	3.78×10^{-2}
		EOC	20-12	11	6.3×10^{-3}	High	
16	Check procedure if vital bus is not restored	EOM	20-7b	2	1.25×10^{-3}	High	1.28×10^{-2}
		EOC	20-11	2	1.3×10^{-3}	High	

Table 6. Execution Recovered, P_{ER} for small mobile GTG

Critical Step No.	Recovery Step No.	Action	HEP (Critical)	HEP (Rec)	Dep.	Conditional HEP (Recovery)	Total for Step
09		Deployment of small GTG in front of auxiliary building.	8.59×10^{-3}				1.68×10^{-5}
	16	Check procedure if vital bus is not restored		1.28×10^{-2}	MD	1.96×10^{-3}	
10		Operator checks status of circuit.	2.53×10^{-2}				4.95×10^{-5}
	16	Check procedure if vital bus is not restored		1.28×10^{-2}	MD	1.96×10^{-3}	
11		Connect powerline to 480V for small GTG.	7.13×10^{-2}				1.40×10^{-4}
	16	Check procedure if vital bus is not restored		1.28×10^{-2}	MD	1.96×10^{-3}	
14		Energize mobile small GTG.	3.78×10^{-2}				7.40×10^{-5}
	16	Check procedure if vital bus is not restored		1.28×10^{-2}	MD	1.96×10^{-3}	
		Total Unrecovered	**1.43×10^{-1}**	**Total Recovered**			**2.80×10^{-4}**

The P_{exe} and P_{ER} HEPs for large mobile GTG and primary FLEX pump were also calculated using the aforementioned steps.

4. Results and Discussion

The calculated HEPs as shown in Table 7 demonstrate that our results were different from the previous work [5] as well as NEI 16-06 guide [4]. The previous work found the HEP of a large mobile GTG, 2.48×10^{-2} is higher than a small mobile GTG, 5.35×10^{-3}. The former author concluded that the small mobile GTG is relatively more effective due to the opportunity to improve response times, simplify human actions, and utilize robust equipment in robust locations, as a mitigation strategy for extended SBO [5]. In contrast, we calculated almost same HEPs for small and large mobile GTG, the values are 8.73×10^{-3} and 8.80×10^{-3} respectively.

Table 7. Comparison of HEP Results

Our HEP Results Summary				
		P_{cog}	P_{exe}	Total HEP
Small GTG	Without Recovery	4.0×10^{-2}	1.43×10^{-1}	8.73×10^{-3}
	With Recovery	8.45×10^{-3}	2.80×10^{-4}	
Large GTG	Without Recovery	4.0×10^{-2}	1.76×10^{-1}	8.80×10^{-3}
	With Recovery	8.45×10^{-3}	3.46×10^{-4}	
Primary FLEX Pump	Without Recovery	4.0×10^{-2}	2.31×10^{-1}	8.90×10^{-3}
	With Recovery	8.45×10^{-3}	4.53×10^{-4}	
Previous Work HEP Results Summary [5]				
Small GTG	Without Recovery	2.0×10^{-3}	1.18×10^{-1}	5.35×10^{-3}
	With Recovery	2.9×10^{-4}	5.06×10^{-3}	
Large GTG	Without Recovery	2.0×10^{-3}	1.98×10^{-1}	2.48×10^{-2}
	With Recovery	2.9×10^{-4}	2.45×10^{-2}	
Primary FLEX Pump	Without Recovery	2.0×10^{-3}	2.07×10^{-1}	6.49×10^{-3}
	With Recovery	2.9×10^{-4}	6.20×10^{-3}	
NEI 16-06 Guide HEP Results Summary [4]				
FLEX Generator	Without Recovery	2.0×10^{-3}	1.18×10^{-1}	5.35×10^{-3}
	With Recovery	2.9×10^{-4}	5.06×10^{-3}	

At the present time, there are deficient data and procedures of FLEX that affected the HEP calculation. It is obligatory to develop precise procedures if anyone wants to get more accurate HEP results. Henceforth, it could not be realistic to suggest now which portable GTG is more useful due to lack of enough information as well as experience on FLEX equipment. On the contrary, the Electric Power Research Institute (EPRI) has started work for the development of portable equipment failure frequency data and enhancements to human reliability analysis methods [11]. One of the potent challenges in this research was to maintain RCP seal integrity under extended SBO and further study is required.

5. Conclusion

Currently, Korea Hydro & Nuclear Power is establishing a multi-barrier accident coping strategy (MACST) as a part of the accident management plan (AMP). The embarking nuclear power countries could either adopt or adapt this Korean strategy for preventing and mitigating severe accident to improve plant safety and operations. The strategy may incorporate at least one large portable DG/site, at least one small portable DG/unit, at least two FLEX pumps (primary & secondary)/unit and other crucial equipment. We also recommend the extension of battery capacity which could be a potent way to cope in response to an extended SBO. For instance, the APR1400 design of Shin Kori 5 & 6 units has already extended their battery capacity to 16 hours. At the same time, a cost-benefit analysis could be performed to optimize the use of portable equipment under beyond design basis accidents. For example, the typical cost to U.S nuclear industry for implementing the FLEX program was in the range of \$20 to \$40 million USD per unit. In contrast, preliminary risk assessments showed up to a 30% reduction in core damage frequency depending on plant design after the implementation of FLEX [12]. It is important to realize that the utility may entail revising the ongoing training programs to ensure ample staffing for handling the FLEX equipment. On the other side, there may also require to address any inadvertent consequences due to the implementation of FLEX equipment like impact to the existing plant design bases, physical & cyber security, maintenance rule implementation etc.

ACKNOWLEDGMENTS

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