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Current Status and Future Plans on Estimation of Human Error Probabilities of FLEX/MACST Actions

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1. Introduction

After the Fukushima accident, the multi-barrier accident coping strategies (MACST) are being implemented as one of post-Fukushima actions for copying with Beyond-Design-Basis External Events (BDBEE) which is called as diverse and flexible mitigation strategies (FLEX) in the U.S. To support risk-informed decision making, the risk benefit of FLEX/MACST implementation needs to be assessed by modeling into a Probabilistic Safety Assessment (PSA). However, it is not easy to calculate the failure risk of FLEX/MACST implementation since portable equipment for FLEX/MACST is new system and most of this equipment failure criteria are related to human action. The value of portable system failure risk can be changed due to Human Error Probabilities (HEP) of FLEX/MACST activities. Thus, a general guideline for estimating the FLEX/MACST HEP should be provided.

Current Human Reliability Analysis (HRA) have limitations when applying to FLEX/MACST activities. First, some quantified values (i.e. transportation, connection of portable equipment, etc.) are not addressed by existing HRA methods. In this case, engineering judgement is usually used to find the unknown HEP value based on generic data from other industries. However, this method has been argued the uncertainty of their results from subjective assessment. To validate the result from engineering judgement, KAERI is preparing an expert elicitation method for estimating the HEP of FLEX/MACST actions.

The objective of this paper is to narrow down the expert elicitation scope of specific human activities. This would allow us to conduct expert elicitation process in a cost and time effective way. To do this, this study investigates current status of FLEX/MACST HEP estimation methods. The narrow-downed FLEX/MACST activities are listed for expert elicitation. Additionally, this paper describes further considerations for developing well-structured HRA method of FLEX/MACST human activities.

2. Current status of FLEX/MACST HEP methods

In the beginning, NEI suggested the streamlined approach for crediting portable equipment [1]. The NEI developed simple decision trees to estimate HEP of FLEX, which heading of the tree consists of four factors such as time margin, command and control, environment factors and equipment availability. The final HEP can be calculated by multiplying basic HEP and the value of four factors. The base HEP is assigned as 1.0E-01 from NUREG-1792. Each factor is divided into two or three statuses. For example, time margin is categorized by inadequate, nominal (1.0) and expansive (0.5) status depending on the availability of sufficient time to perform the mitigation strategy. These statuses are assigned each multiplier values expressed in the brackets. In case of inadequate time margin it is directly led to a failed action, so in that case, the final HEP is 1.0.

The U.S. NRC utilizes expert judgment to support HRA of FLEX. They assumed the non-FLEX-designed accident scenarios and FLEX-designed type scenarios. Each scenario decomposed into several human activities, which experts estimated the HEP of the human activities. In addition, the Performance Shaping Factors (PSFs) of each human activity were developed and quantified by experts. The human activities of NRC report were summarized as Table I. In summary, the NRC strategy is listing all possible human activities with PSFs during deploying/implementing/sustaining FLEX strategies, and experts estimates the HEPs of each activities and PSFs.

The other way of FLEX/MACST HEP estimation is using analytic method based on conventional HRA technique such as Cause-Based Decision Tree Method (CBDTM), an Integrated Human Event Analysis System (IDHEAS), K-HRA for diagnostic HEP and Technique for Human Error Rate Prediction(THERP) for execution HEP. The EPRI [2] and KAERI [3-4] also used this method for estimating HEP of MACST/FLEX. They specified the human activities of MACST/FLEX and estimated HEP by generic data from conventional method. Due to the lack of execution task failure data, some tasks were estimated by engineering judgement or replacing similar tasks. The human activities from EPRI and KAERI reports are summarized as Table I. We are also considering this analytic method for estimating HEPs of MACST. If we use this strategy, the lack of execution tasks and some limited activities data will be estimated by expert judgement.

Japan is also trying to estimate HEPs based on task analysis of FLEX-like strategies for a tsunami PSA. According to the presentation materials form CRIEPI [5], they plan to use THERP data. In case of lack of execution task failure data, they will develop the HEP of these tasks.

Table I: Summary of FLEX/MACST Human Actions

Activity/ Work flow — NRC [2]

Specific tasks	Non-FLEX-designed: Scenario 1.1	Non-FLEX-designed: Scenario 1.2	FLEX-designed with natural hazards: Scenario 2
Action 1: Use of Portable generator			
Task 1.1 Decide to use portable generator	Diagonostic HEP	ELAP declaration	ELAP declaration
Task 1.2 Transport and stage portable generator (and cables)	Action HEP	Action HEP	Action HEP
Task 1.3 Connect portable generator	Action HEP	Action HEP	Action HEP
Task 1.4 Operate the generator	Diagonostic +Action HEP	Diagonostic +Action HEP	Diagonostic +Action HEP
Action 2: Use of Portable pump			
Task 2.1 Decide to use portable pump	Diagonostic HEP	Diagonostic HEP	Diagonostic HEP
Task 2.2 Transport and stage portable pump	Action HEP	Action HEP	Action HEP
Task 2.3 Connect portable pump	Action HEP	Action HEP	Action HEP
Task 2.4 Start and operate the pump	Diagonostic +Action HEP	Diagonostic +Action HEP	Diagonostic +Action HEP
Action 3: Refilling water storage tanks using alternate water sources			
Task 3.1 Decide to use alternative water source	Diagonostic HEP	Diagonostic HEP	Diagonostic HEP
Task 3.2 Use alternative water source to fill water tank	Action HEP	Action HEP	Action HEP
Action 4: ELAP declaration			
Task 4.1 Declare ELAP	_	Diagonostic HEP	Diagonostic HEP
Action 5: deep load shed			
Task 5.1 Deep load Shed (Missing any of the 18 breakers)	_	Diagonostic +Action HEP	Diagonostic +Action HEP
Action 6: Restoration of equipment from direct current load shedding			
Task 6.1 Decide to restore equipment from dc load shed	_	Diagonostic HEP	_
Task 6.2 Restore equipment	_	Action HEP	_
Action 7: Removal of debris (in the FLEX-designed scenario)			
Task 7.1 Not removing the debris within the time margin	_	_	Action HEP

Activity/ Work flow — EPRI (2018) [3]

Specific Tasks	FLEX
Action 1: Declaration of ELAP (by 1 hours) and transfer into the ELAP procedure/initiation of FLEX strategy	
Declare ELAP by 1 hours (clear procedures)	Cognition(CBDT) + Cognition(IDHEAS Delay Implementation) HEP with/without recovery
Declare ELAP by 1 hours (Judgement-based)	Cognition(IDHEAS Delay Implementation) HEP with/without recovery
Action 2: Decision to Deploy Equipment in Non-FLEX Strategies	
EOP well proceduralized	Cognition HEP will be considered, but was not estimated in this report.
EOP-judgement-based cues	
Action 3: Transportation, installation and testing of portable pump.	
Deploy/Align Flex Pump for PRV Injection	Execution(THERP) HEP with/without recovery
Action 4: Deep load shed initiated by ELAP declaration	
Perform ELAP DC Load Shed	Execution(THERP) HEP with/without recovery
Action 5: Depressurization and start of portable pump for water injection	
Inject to RPV with FLEX Pump	Execution(THERP) HEP with/without recovery
Action 6: Refueling a generator	
Refuel to FLEX DG	Cognition(CBDTM)+Execution(THERP) HEP

Activity/ Work flow — KAERI [4-5]

Specific tasks	MACST Internal scenario	MACST External scenario
Action 1: Situation Assessment and Planning for ELAP Event based on EOP (MCR)		
Diagnosis and Planning of the Event	Diagonostic HEP from Max(K-HRA, CBDTM)	
Action 2: Direction/Instruction of Deploying Portable Generator to Local Emergency Response Team		
Task Order to Local emergency response team	Diagonostic HEP from Max(K-HRA, CBDTM)	
Action 3: Preparation of Essential Equipment/Tools/Components (e.g., Cable, Lights, Tools, etc.) (Local Staff)		
Preparation of essential equipment/tools/components	Execution HEP from K-HRA	
Action 4: Selection/Loading, Transportation, and Unloading of the Portable Equipment (Local Staff)		
Selection and Loading of the equipment	neglected	Intensity of external events needs to be considered
Transportation and Unloading of the equipment		
Action 5: Installation/Connection of the Portable Equipment (i.e., cables and electrical buses) (Local Staff)		
Installation/Connection of the portable equipment	Connection, omission, selection error from THERP or K-HRA	
Action 6: (Report to the MCR on the Completion of Installation/Connection)		
Report to the MCR on the completion of installation	Omission error of report from K-HRA	
Action 7: Startup of the Portable Generator and Closing the Breaker to Supply Electrical Power (Local Staff)		
Startup of the generator	Omission & commission error of the generator startup	
Closing the breaker	Omission & commission error of putting circuit breaker in	
Action 8: (Check by the MCR and Follow-up Actions) (MCR)		
(Check by the MCR and Followup Actions)	Failure of coordination with MCR	

	NRC [2]	EPRI (2018) [3]	KAERI [4-5]
Reactor Type	Reactor types(PWR and BWR) were not identified as a catergory for estimating HEP	BWR	PWR
Approches	Expert eliciation method (Action 6 and 7 is not estimated by expert elicitation)	Coventional HRA method (CBDTM, IDHEAS and THERP)+Engineering judgment	Coventional HRA method (CBDTM, THERP and K-HRA) +Engineering judgment
Ways of Use of Portable Equipment	Not prestaged and brought from the FLEX building outside the fence	prestaging of portable equipment , onsite	1)Pre-staging of portable equipment 2)Deploying the equipment by the initial or 3) by the off-site emergency response team

Performance Shaping Factors (PSF)

NRC [2]		EPRI (2018) [3]	KAERI [4-5]	
(1) weather factors	*Notes_secenarios	(1) Complexity	General PSF for internal event	Additional factors for external events
(2) information availability and reliability	Non-FLEX-designed scenario: the plant loses important safety functions without external hazards.	(2) Special Equipment	(1) Procedure:transparency/multiple procedures/tasks	(10) Integrity of the storage facility, travel paths, and local places
(3) tools and parts		(3) Human-machine interface	(2) Training	
(4) human-system interface (HSI) (indicators and controls)	Scenario 1.1: one EDG is out of service and the second EDG is running but may go down at any time. The Technical Support Center (TSC) decides to use the portable FLEX DG to power the bus associated with the out-of-service EDG and use the portable FLEX pump to provide RCS injection.	(4) Procedures	(3) Status of preparedness of essential tools/ components for each of equipment	(11) Intensity of the earthquake, and the frequency and duration of the aftershock
(5) procedures		(5) Special fitness needs		
(6) training		(6) Staffing	(4) Transparency of equipment and clearness of labeling	(12) Potential for Intervention of Debris/Obstructions on the travel paths
(7) teamwork factors	Scenario 1.2: the second EDG is lost and may not come back soon, leading to the decision to declare ELAP and shed the load. After ELAP and load shed, offsite power returns, and the plant has the option of restoring power from the load shed.	(7) Communications	(5) Road status	
(8) scenario familiarity		(8) Equipment Accessibility	(6) Effect of weather	(13) Effect of external events on the activities at local places (impact of working condition)
(9) multitasking, distraction, and interruption		(9) Environmental Factors	(7) working environment: lighting, narrowness, etc.	
(10) task complexity		(10) Cue and Indications	(8) Quality of MMI of the portable generator	(14) Integrity/Availability of the offsite emergency personnel
(11) mental fatigue and stress	FLEX-designed scenario: some external hazards lead to SBO and loss of both DGs.	(11) Training and Experience	(9) Availability/Reliability of the Communication System	
(12) physical demands		(12) Workload, Pressure, and Stress		

3. Future strategies for estimating HEP of MACST

Based on the Table I, we selected the MACST human activities for conducting an expert elicitation. As mentioned Section 2, two track strategies are considered: 1) All defined tasks' HEP judgement by experts (Scenarios-based approach) and 2) Expert judgement on limited data in the conventional methods (Limited data-based approach).

3.1. Human Activities for scenarios-based approach

In Table I, each organization assumed FLEX/non-FLEX scenarios, but the criteria of scenarios were ambiguity. In case of Korea, there are no clear procedures of using portable equipment during non-FLEX scenarios. However, the NRC and EPRI considered the non-FLEX scenarios. Thus, this paper suggests four basic scenarios for estimating HEP of MACST activities: 1) MACST strategy within a BDBEE Scenario; 2) MACST strategy within an internal event; 3) Non-MACST strategy with pre-staged equipment; and 4) Non-MACST Strategy post initiating event. This categorization of scenarios is suggested from KHNP-EPRI workshop in 2019.

Actually, FLEX/MACST actions have a large number of steps so the results may be unrealistically high. Thus, grouping of each steps as similar action is necessary. Table II describes the specific tasks which are to be estimated by experts. This table can be used for a base example to get HEP by expert judgement. However, before getting the HEP value, expert's brainstorming workshop should be held for understanding each tasks' meaning and improving or editing all defined tasks.

Table II. Human Activities for scenarios-based approach

MACST Scenarios (Internal/External)	**Non-MACST Scenarios (Internal/External)**
Action 1: Situation Assessment	
Declare ELAP by 1 hours (clear procedure)	Decision of deployment (EOP well-proceduralized)
Declare ELAP by 1 hours (Judgement-based)	Decision of deployment (EOP-judgement-based cues)
Action 2: Deep Load shedding	
Diagnostic of what/where is the 18 breakers	
Communication failure between MCR and local panel	
Performing DC Load shed by local panel	
Action 3: Direction/Instruction of Deploying Portable Generator to Local Emergency Response Team	
Omission of Task initiation	
Error of multi-group communication	Error of wrong communication
Time delayed direction/instruction	X
Command and control error	X
Action 4: Preparation of Essential Equipment/Tools/Components	
Omission of essential tools/components	
Action 5: Selection/Loading of the Portable Equipment	
Selection/loading of wrong equipment from the storage facility	
Action 6: Transportation, and Unloading of the Portable Equipment	
Transport and unload failure by Debris/obstruction	Damage equipment during transportation/unloading
Action 7.1: Installation/Connection of the Portable generator	
Inadequate/loose connection	
Connection to wrong object (bus)	
Action 7.2: Installation/Connection of the Portable pump	
Deploy/Align Flex Pump for PRV Injection	
Inadequate/loose connection	
Connection to wrong water source/cables	
Action 8: (Report to the MCR on the Completion of Installation/Connection)	
Omission of report on completion of connection work	
Action 9.1: Startup of the Portable Generator and Closing the Breaker to Supply Electrical Power	
Omission & commission error of the generator startup	
Omission & commission error of putting circuit breaker in	
Action 9.2:Depressurization and start of portable pump for water injection	
Inject to RPV with MACST Pump	
Action 10: (Check by the MCR and Follow-up Actions) (MCR)	
Failure of coordination with MCR	
Action 11.1: Refilling water storage tanks using alternate water sources	
Decide to use alternative water source	
Use alternative water source to fill water tank	
Action 11.2: Refueling a generator	
Decide to refueling	
Refuel to MACST DG	
Action 12:Restoration of equipment from direct current load shedding	
X	Decide to restore equipment from dc load shed
	Restore equipment
Action 13: Removal of debris	
Not removing the debris within the time margin	X

3.2. Covering the limited data based approach

Based on comparison of each report [2-6], unknown data of FLEX/MACST action is identified in Table III.

Table III. List of unknown data in FLEX/MACST activities

Lack of execution task failure data [6]
Connect hose to equipment
Level/pressure/temperature control-MCR
Level/pressure/temperature control-local
Operation of equipment on a local panel
Operation of equipment -control located on equipment
Loading/unloading portable equipment
Transportation of portable equipment (vehicle)
Operation of a vehicle-onsite
Transportation of portable equipment-offsite
Install/remove section of hard pipe or a flange
Make a temporary power connection-household
Clear debris from haul path
Placement/installation of a portable fan
Installation of temporary HVAC ducts
Prop open door

Locally confirm correct rotation of equipment
Deep load shed
Refueling a generator
Refilling water storage tanks using alternate water sources
Restoration of equipment from DC load shedding
Lack of cognition failure data
Failure of declaration of ELAP (by 1hours) based judgement
Failure of decision to deploy equipment in non-FLEX strategies (EOP-judgement based cues)
Failure of decision to restore equipment from dc load shed
Failure of decision to refuel a diesel generator
Failure of decision to refill a water storage tanks

4. Potential Challenges for HEP Estimation in FLEX/MACST Activities

4.1. Additional PSF considerations

Despite of various PSFs depicted in Table I, additional PSFs might be considered. The lists of additional consideration for PSFs are below:

1) Crew availability and working familiarity,
2) Mental pressure or stress during extreme or long lasting situation,
3) Categorization and assign multipliers for Damage State Bin (DSB) depending on the type of external events (i.e., typhoon, heavy rains as well as seismic and tsunami events),
4) Assessing the probability of failure to properly prioritize tasks when the procedure does not specify an order,
5) Multi-unit/Multi-site coordination,
6) Long term control actions, and
7) Organization culture which can represent resilience of safety culture.

4.2. Necessity of PSF categorization

Since these PSFs have dependencies, these PSFs are need to categorize generalized PSFs for clarity of HEP estimation.

4.3. PWR specific scenario development

Plant-specific accident sequence analysis scenarios should be developed because of key safety functions modified by FLEX equipment and change of initiating events which can be successfully mitigated by using FLEX strategy. Thus, in case of Korea, PWR based specific scenario development is needed before starting to expert elicitation process.

4.4 Dependencies

Dependencies between mitigating system and FLEX equipment should be considered. For example, the depressurization of RPV is required to implement FLEX Pump.

Time phase dependencies and potential multi-unit impacts need to consider for evaluating HEP. The number of prepared portable equipment and external hazards can affect to mitigate accident of multi-units.

5. Conclusions

This paper investigated the current research and future strategies of FLEX/MACST activities for estimating HEP. The HEP of FLEX/MACST activity is not easy to estimate due to the unknown activities and hard difficulties of performing human activities since the situation of FLEX/MACST deployment is not nominal but usually with external nature disasters. With investigating the current status of the HEP, we narrowed down the human activities in FLEX/MACST. The results of this study will be helpful to perform a well-structured expert elicitation.

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