

Evaluation of Emergency Response Organizations for Coping with Multi-unit Accidents assuming Staffing Availability

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1. Introduction

Beyond design-basis external event (BDBEE) mitigation strategies such as FLEX in the U.S. [1] and the multi-barrier accident coping strategy (MACST) in Korea [2] rely on portable equipment as the principal means of restoring critical safety functions after the loss of fixed systems. They also require operating guidelines and, equally important, augmented emergency response organizations (EROs) that can be mobilized and coordinated during the event.

A distinctive feature of BDBEEs is that accidents may progress simultaneously in several units of one site. Existing human reliability analysis (HRA) methods for portable equipment operations [3,4,5] largely adopt a single-unit framework centered on diagnosis and execution errors; they do not systematically model the cooperative activities between the multiple organizations involved, nor the dependencies among units undergoing concurrent accident progression.

A multi-unit HRA (MU-HRA) method addressing these elements has recently been addressed at KAERI [6,7]. Using this method, the present study defines three representative ERO structures for a multi-unit site — unit-level, station-level and site-level — and estimates the human and organizational failure probability of each structure for an extended loss of AC power (ELAP) scenario. The evaluation is carried out under the explicit assumption that sufficient number of emergency personnel is available on site at the required time, so that the comparison isolates the effect of the command-and-control (C&C) structure itself rather than that of resource competition.

2. Emergency Organization Structures

Three ERO structures are defined for the management and operation of portable equipment under BDBEE conditions:

- Type 1 (unit-level): each reactor unit has a dedicated team for portable equipment deployment and operation, mobilized directly from the main control room (MCR) of that unit.
- Type 2 (station-level): a pair of units shares a pool of personnel, whose allocation to a unit is coordinated by the technical support center (TSC), the higher-level C&C organization of the station.

- Type 3 (site-level): three or more units share a site-level pool, allocated under the coordination of the emergency operation facility (EOF), the top-tier C&C organization of the site.

The organizational entities common to all three types are the EOF, the TSC, the MCR, the local operators (LO) of each MCR shift team, and the local safety center (LSC), which transports and installs portable equipment. The LSC consists of the LSC headquarters (LSC-HQ) at the equipment storage facility (ESF), the LSC drivers (LSC-DR) who transport the equipment, and the LSC field operators (LSC-FO) who lay and connect cables and hoses. Fig. 1 summarizes the resulting task flow and C&C chain of each type.

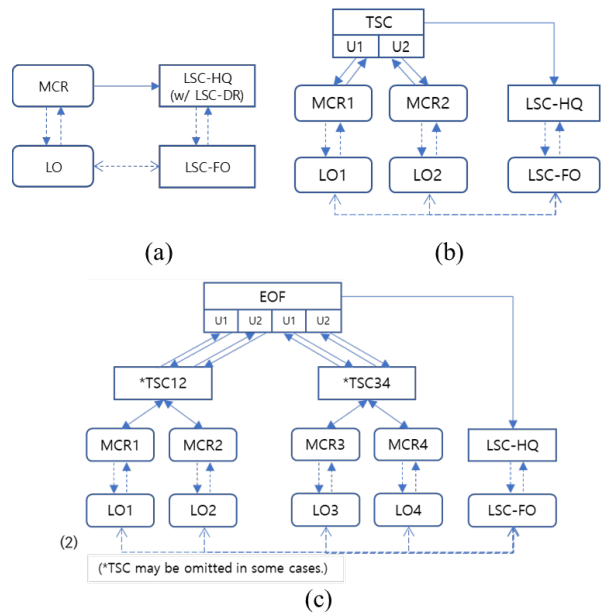


Fig. 1. C&C chain and task flow of the three ERO structures.

From an HRA viewpoint the critical inter-organizational communication activities are grouped into three categories: (i) the initial request from the MCR, via the coordinating organizations, to the LSC-HQ to deploy and install the required equipment at a designated unit; (ii) fieldwork communication in which the field work supervisor or LO instructs the LSC-FO to lay and connect cables or hoses; and (iii) sustained communication between the MCR and the LOs for status checking and operational control. In this study only category (i) is quantified as an inter-team

communication task. Category (ii) is treated as intra-team task execution, because the field supervisor instructs the LSC-FO directly and verifies the result on site, and category (iii) is covered by the execution error of the LOs, who act on the field operating procedure.

3. The MU-HRA method

The technical elements of the method are classified into diagnosis errors, communication errors arising from inter-organizational cooperation, and execution errors [6].

3.1. Diagnosis Error Probability (DEP)

Whether the diagnosis is made in the individual MCR or in the TSC/EOF, it is based on status information collected from one specific unit, so the conventional single-unit framework applies. Because the criteria for deciding to operate portable equipment are written in a rule-based manner consistent with the existing emergency operating procedures, the time-based K-HRA/Rev.1 method [8] was adopted. Given the large uncertainty in the time required for deployment, it is assumed that at least about one hour of time margin must remain for situation assessment and response planning in order to credit diagnosis; the corresponding nominal value is 1.0E-3. The DEP is then

$$DEP = P_0 \times M_{PROC} \times M_{HSI} \times M_{train} \times M_{multi} \quad (1)$$

where the three multipliers are the K-HRA/Rev.1 PSF multipliers for procedure quality, human-system interface quality and training/experience, and $M_{multi} = 2$ is applied when several procedures must be used concurrently, following the EPRI CDBT guideline [9].

3.2. Communication Error Probability (CEP)

Most HRA methods do not treat inter-organizational cooperation explicitly. IDHEAS-ECA [10] does, through the inter-team coordination and communication (ICC) macrocognitive function, and its ICC cognitive failure mode (CFM) is therefore used here. A critical task is defined as a single essential request or direction transmitted from one organization to another, and one ICC CFM is assigned per critical task:

$$CEP = P_{ICC} = P_{ICC,Base} \cdot (1 + \sum (w_i - 1)) \quad (2)$$

The base value is taken from the ICC base HEPs by task complexity in Table I. The PSF weights are taken from Tables B-4 to B-15 of IDHEAS-ECA with two modifications. First, attributes whose weight is 1.1 or 1.2 are excluded, their contribution to the CEP being small relative to the other factors. Second, for attribute MT10 (concurrently communicating or coordinating multiple distributed individuals or teams) IDHEAS-ECA does not specify how the weight varies with the number of coordinated parties, which is precisely what a multi-unit application needs. A weight of 2 is therefore assigned when two units simultaneously

require deployment and a weight of 5 when three or more units do.

Table I: Base HEPs for the ICC CFM by task complexity (adapted from IDHEAS-ECA [10], Table B-3)

PSF attribute of the ICC CFM	Base HEP
C40 No impact – clear, streamlined, crew-like communication	0
C41 Complexity of information communicated	
– Simple (e.g. notifying/requesting to ex-MCR)	1.5E-3
– Moderate	1.0E-2
– High	5.0E-2
– Extremely high	1.0E-1
C42 Complex or ambiguous command-and-control	1.0E-2
C43 Complex or ambiguous authorization chain	1.0E-2
C44 Coordinate activities of multiple diverse teams	1.0E-2

3.3. Execution Error Probability (EEP)

The execution error covers the whole chain from the receipt of the installation request to the operation of the equipment, and is decomposed into five stages:

$$EEP = EEP_{prep} + EEP_{trans} + EEP_{conn} + EEP_{align} + EEP_{oper} \quad (3)$$

Each term is the product of a nominal HEP, a count of items or actions, correction factors for procedure quality, training and stress/fatigue, and a recovery failure probability (RFP). The nominal values adopted are: 1.0E-3 per essential item or vehicle omitted in the preparation stage [8]; 5.0E-5 per mile (1.6 km) of travel for vehicle collision or overturning, from the EPRI FLEX HRA methodology [3]; 2.0E-2 per coupling point for the connection stage, combining omission, selection and improper-coupling errors from THERP [11], reducible to 1.3E-2 where only improper coupling is credible; and 5.0E-3 and 2.0E-3 per component for field and MCR actions, respectively, in the alignment and operation stages. Recovery is credited using K-HRA/Rev.1 RFPs, i.e. 1.61E-1 for an independent verification explicitly specified in the field procedure, and 2.0E-2 (high stress) or 5.0E-2 (extremely high stress) for later detection from the MCR, provided the available recovery time exceeds about 1.5 times the required action time. No recovery is credited for the transportation stage, since a collision or overturning disables the vehicle itself.

3.4. Treatment of Multi-unit Concurrency

The effect of concurrent demands from several units enters the model at three points. For the preparation stage, the effect is carried by the communication error through MT10. For transportation, a departure delay of about 20 min is assumed for each subsequent vehicle, and complete dependency ($HEP = 1.0$) is assumed either when the same LSC-DR drives the preceding and the subsequent vehicle, or over a road segment so narrow that only one vehicle can pass at a time. For connection, alignment and operation, inter-unit independence is assumed as long as the LSC-FO and LO personnel are assigned per unit — which is the staffing-availability premise of this study.

4. Case Study: Deployment of portable generator (PG) under ELAP

The method was applied to the task “deployment and operation of the portable generator (PG)” under an ELAP scenario, for each of the three ERO structures and for both single-unit and multi-unit concurrent events. The baseline conditions are:

- All personnel required for the initial response are present on site.
- The allowed time from reactor trip to AC power restoration is 8 h; the ELAP condition is declared 30 min after trip, which is taken as the cue; and the time required from the deployment request to the completion of start-up is 150 min [12].
- Satellite phones are available, non-safety telephones and page phones being assumed lost.
- Instrumentation needed for diagnosis is not lost, and no debris obstructs the transport route or the installation site.

The time margin for error recovery is therefore $480 - 180 = 300$ min, comfortably longer than the 150 min required, so recovery may be credited for every stage except transportation. The stress level is taken as extremely high, reflecting night-time work under a BDBEE, while procedure quality and training level are nominal

4.1. Diagnosis Error Probability (DEP)

With high procedure quality and medium HSI and training/experience levels, Eq. (1) gives $DEP = 1.0E-3 \times 0.597 \times 2 = 1.19E-3$. If the procedure gives ambiguous guidance on the ELAP declaration criteria, the procedure quality drops to medium and the multiplier increases by roughly one order of magnitude, giving $1.12E-2$. Since the diagnosis is performed in the individual MCR in all three structures, and independently per unit, the DEP is common to the three types and identical for single-unit and multi-unit events. The value $1.19E-3$ is used below.

4.2. Communication Error Probability (CEP)

The quantified critical task is the instruction “deploy and connect the PG to the designated unit”, transmitted from the MCR to the LSC-HQ. Its complexity is judged simple, giving a base value of $1.5E-3$ (Table I). The PSF attributes that differentiate the three structures are listed in Table II. TE2 (training conducted only for certain organizations or limited to specific scenarios) applies to all three. In Type 2 the request passes through the TSC, an organization with lower situational awareness than the MCR, so items such as the dispatch of the LSC-FO may be omitted or delayed; TF3 (poor information management in multiple-team tasks) is therefore added. In Type 3 the chain is extended further to the EOF, and TF1 (distributed or dynamic teams) is added as well. For concurrent events, MT10 is applied on top of the single-unit set.

Table II: PSF attributes applied to the ICC CFM and the resulting CEP by organization type

PSF attribute (weight)	Type 1	Type 2	Type 3
TE2 Inadequate training practicality (1.5)	√	√	√
TF3 Poor information management in multiple-team tasks (2)	–	√	√
TF1 Inadequate team – distributed/dynamic teams (2)	–	–	√
MT10 Concurrent coordination, two units (2) *	√	√	√
MT10 Concurrent coordination, three or more units (5) *	√	√	√
CEP – single-unit event	2.25E-3	3.75E-3	5.25E-3
CEP – two units involved	3.75E-3	5.25E-3	6.75E-3
CEP – three or more units involved	8.25E-3	9.75E-3	1.13E-2

* applied to multi-unit concurrent events only.

The resulting CEPs are given in the lower part of Table II. Relaying the request through the site-level top organization rather than directly from the MCR to the LSC raises the single-unit CEP by a factor of about 2.3, and concurrent demand from three or more units raises it by a further factor of 2 to 4 relative to the single-unit case.

4.3. Execution Error Probability (EEP)

Two vehicles are assumed, one carrying the generator and power cables and one carrying lighting equipment, and three coupling points are counted: the PG to the plant electrical system, the fuel transfer pump, and the power cable between the PG and that pump. The alignment stage covers the 4.16 kV and 480 V bus breakers, the charger feeder breaker and the two fuel-supply valves; the operation stage covers the PG engine start and the fuel transfer pump operation. Table III gives the resulting stage-wise values. The connection error dominates, and is reduced from $1.50E-2$ to $2.4E-3$ when an independent verification by the on-site supervisor is explicitly specified in the field procedure; the total EEP of $1.22E-2$ credits that verification. Independent verification of the alignment actions was conservatively not credited, on the assumption that supervisory oversight in the field is very limited.

Table III: Stage-wise EEP for the PG deployment task

Stage	Evaluation	EEP
Preparation	$1.0E-3 \times 2 \times 5 \times 5.0E-2$	$5.0E-4$
Transportation	$5.0E-5 \times 2 \times 5$ (no recovery)	$5.0E-4$
Connection	$2.0E-2 \times 3 \times 5 \times 5.0E-2 \times 0.16$	$2.4E-3$
Alignment	$(5.0E-3 \times 3 + 5.0E-3 \times 2) \times 5 \times 5.0E-2$	$6.25E-3$
Operation	$(5.0E-3 \times 1 + 5.0E-3 \times 1) \times 5 \times 5.0E-2$	$2.50E-3$
Total		$1.22E-2$

Because sufficient personnel are assigned to each unit and the time available is long, the transportation delay of about 20 min per subsequent vehicle has a negligible effect. The EEP is therefore common to the three structures and to both event scales.

4.4. Results and Discussion

Table IV collects the results. The DEP and the EEP do not differentiate the structures, for the reasons given above; the discriminating term is the CEP. In relative terms the site-level structure is the least reliable of the three: its total HEP is about 19 % higher than that of the unit-level structure for a single-unit event and about

14 % higher for concurrent events in three or more units. In absolute terms, however, the spread across the whole matrix is modest, from 1.56E-2 to 2.47E-2, because the EEP arising from the many field activities is large compared with both the DEP and the CEP.

Table IV: HEP results by organization type and event scale

Type	Event scale	DEP	CEP	EEP	Total HEP
1	Single unit	1.19E-3	2.25E-3	1.22E-2	1.56E-2
	Two units involved	1.19E-3	3.75E-3	1.22E-2	1.71E-2
	Three or more units involved	1.19E-3	8.25E-3	1.22E-2	2.16E-2
2	Single unit	1.19E-3	3.75E-3	1.22E-2	1.71E-2
	Two units involved	1.19E-3	5.25E-3	1.22E-2	1.86E-2
	Three or more units involved	1.19E-3	9.75E-3	1.22E-2	2.31E-2
3	Single unit	1.19E-3	5.25E-3	1.22E-2	1.86E-2
	Two units involved	1.19E-3	6.75E-3	1.22E-2	2.01E-2
	Three or more units involved	1.19E-3	1.13E-2	1.22E-2	2.47E-2

Two practical implications follow. First, under the staffing-availability premise the unit-level structure is the most effective, because it minimizes inter-organizational dependency and multi-unit interaction. This conclusion is conditional: where staffing or equipment is limited, as in an extreme external hazard, a higher-level organization is needed to set priorities and allocate resources across units, and the site-level structure then becomes necessary rather than merely more complex. The ERO design should therefore be able to switch between the two modes. Second, and independently of the structure, the dominance of the EEP shows that the larger reliability gain lies in simplifying the numerous field actions required for portable equipment deployment and in securing fixed dedicated systems wherever feasible, so as to reduce reliance on manual portable equipment operation.

The results should be read within the boundary of the stated assumptions. In an actual BDBEE it may take considerable time for off-site emergency personnel to reach the plant, so that staffing at the required time may in fact be insufficient; the hazard may damage instrumentation needed for situation assessment; compound events cannot be ruled out; and debris may obstruct the transport route. Each of these would act on the diagnosis and execution terms as well as on the communication term, and would tend to favour the structures that allow site-level prioritization. Relaxing the staffing-availability premise is therefore the natural next step, and is expected to change the ranking of the three structures rather than merely to scale the numbers.

5. Conclusions

Three representative ERO structures for a multi-unit site were evaluated with the MU-HRA method for an ELAP scenario, assuming sufficient staffing availability. Diagnosis and execution errors were found not to discriminate between the structures under that assumption, whereas the coordination and communication error grows with the length of the C&C chain — by about a factor of 2.3 from the unit-level to the site-level structure — and by a further factor of 2 to

4 when three or more units demand deployment concurrently. The unit-level structure is consequently assessed as the most effective under the stated premise, while the total HEPs of the three structures remain within a factor of 1.6 of each other because field execution errors dominate. Future work needs to consider the variability of multi-unit accident progression, dynamic characteristics of staffing availability, multiple compound events, and obstacles and debris along the transport route, and will seek empirical support for the MT10 weights.

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