A Framework of Human Reliability Analysis Method Considering Soft Control in Digital Main Control Rooms

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Abstract. The operation environment of Main Control Rooms (MCRs) in Nuclear Power Plants has changed with the adoption of new human-system interfaces that are based on computer-based technologies. The MCRs that include these digital and computer technologies are called Advanced MCRs. Among the many features of Advanced MCRs, soft controls are a particularly important feature because the operation action in NPP Advanced MCRs is performed by soft control. Due to the different interfaces between soft control and hardwired conventional type control, different human error probabilities and a new Human Reliability Analysis (HRA) framework should be considered in the HRA for advanced MCRs. Although there are many HRA methods to assess human reliabilities, these methods do not sufficiently consider the features of advanced MCRs such as soft control execution human errors. In this paper, a framework of HRA method for evaluation of soft control execution human error in advanced MCRs is suggested.

Keywords: Advanced MCR, Soft control, Execution human error probability.

1 Introduction

The assessment of what can go wrong with large scale systems such as nuclear power plants is of considerable interest at present, given the past decade's record of accidents attributable to human error. Such assessments are formal and technically complex evaluations of the potential risks of systems, and are called probabilistic safety assessments (PSAs). Today, many PSAs consider not only hardware failures and environmental events that can impact upon risk but also human error contributions [1].

In addition, since the Three Mile Island (TMI)-2 accident, human error has been recognized as one of the main causes of nuclear power plant (NPP) accidents, and numerous studies related to human reliability analysis (HRA) have been carried out such as Technique for Human Error Rate Prediction (THERP) [2], Korean Human Reliability Analysis (K-HRA) [3], Human Error Assessment and Reduction

S. Yamamoto (Ed.): HIMI 2014, Part II, LNCS 8522, pp. 335–346, 2014.
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Technique (HEART) [4], Success Likelihood Index Methodology (SLIM) [5], Human Cognitive Reliability(HCR) [6], A Technique for Human Event Analysis(ATHEANA) [7], Cognitive Reliability and Error Analysis Method(CREAM) [8], and Simplified Plant Analysis Risk Human Reliability Assessment(SPAR-H) [9] in relation to NPP maintenance and operation. Most of these methods were developed in consideration of the conventional type of Main Control Rooms (MCRs) and have been still used for HRA in advanced MCRs despite that the operation environment of advanced MCRs in NPPs has considerably changed with the adoption of new human-system interfaces such as soft controls that are based on computer-based technologies. In other words, these methods that have been applied to conventional MCRs do not consider the new features of advanced MCRs such as soft controls.

Due to the different interfaces between soft control and hardwired conventional type control, different human error probabilities and a new HRA framework should be considered in the HRA for advanced MCRs. Thus, given the absence of a HRA method that considers design features of soft control, the objective of this study is to develop a HRA method for evaluation of soft control execution human error by analyzing the characteristics of soft control in advanced MCRs.

2 Soft Control

2.1 Definition and General Characteristics of Soft Control

In NUREG-CR/6635, soft controls are defined as "devices having connections with control and display systems" that are mediated by software rather than physical connections [10]. This definition directly reflects the characteristics of advanced MCRs, including that the operator does not need to provide control input through hard-wired, spatially dedicated control devices that have fixed functions. Because of this characteristic, the functions of soft control may be variable and context dependent rather than statically defined. [10-11].

2.2 Task Analysis for Soft Control

A soft control task analysis is performed to identify human error modes and develop the framework of a new HRA method considering soft control.

Systematic Human Error Reduction and Prediction Approach (SHERPA) is useful when hierarchical tasks such as human involved tasks and procedures are analyzed [12]. As an example, Fig. 1 shows a task analysis using SHERPA.

The goal of the task is to reset the safety injection and auxiliary feedwater actuation signal. In order to achieve the goal, the operator selects "Reactivity system screen" from the operator console and resets the safety injection signal. For reset of the safety injection signal, there are other subtasks: "Press bypass button from the operator console", "Press the acknowledge button", and finally "Press bypass button using the input device for the safety component". Another subtask, "Reset the auxiliary feedwater actuation signal", performed to reset the safety injection signal, is then analyzed. The subtasks can be rearranged as shown in Fig. 2.

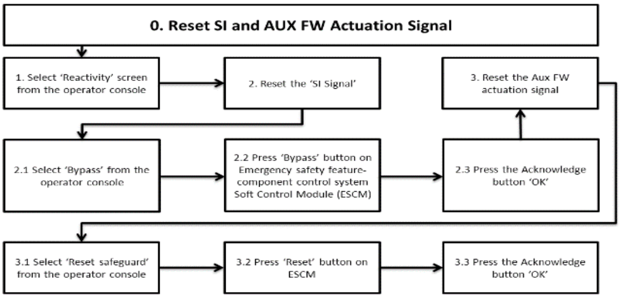


Fig. 1. Task analysis using SHERPA

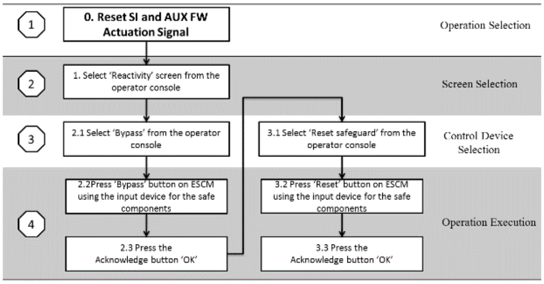


Fig. 2. Sequence analysis of a soft control task

Each subtask is included in one of four sub steps: operation selection, screen selection, control device selection, and operation execution. [11].

2.3 Soft Control Human Error Mode Classification

From the results of soft control task analysis, soft control human error modes already have been identified in several papers. [11, 13].

- Operation omission (E_1): An operator omits performing a sub task when performing a task. (one sub task in a task).
- Wrong object (E_2): An operator selects a wrong device when performing a task.
- Wrong operation (E_3): An operator performs a wrong operation, such as pressing the 'OPEN' button instead of the 'CLOSE' button.
- Mode confusion (E_4): An operator performs a right operation in a wrong mode.
- Inadequate operation (E_5): An operation is executed insufficiently, too early or for too long/short.
- Delayed operation (E_6): An operation is not performed at the right time.

However, soft control human error modes are modified to develop a new framework for the HRA method, as shown in Fig. 3.

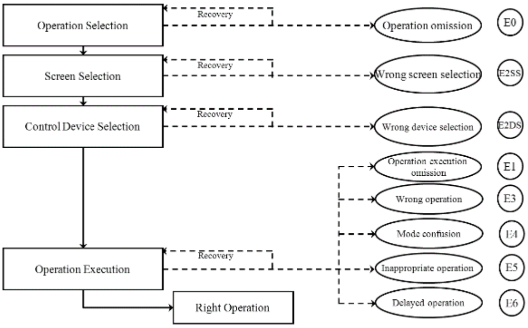
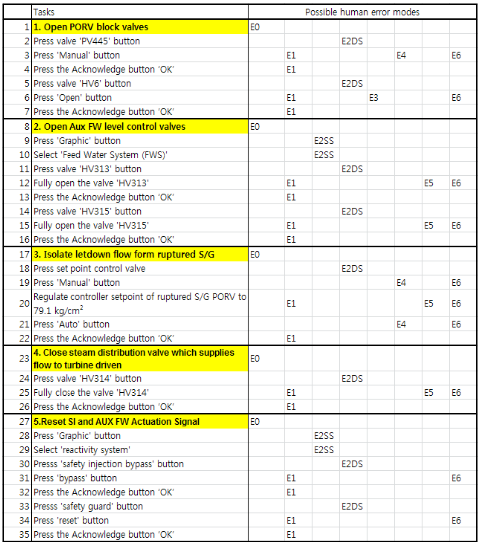


Fig. 3. Soft control human error modes

Operation omission is divided into two kinds of omissions, operation selection omission and operation execution omission, since their error probabilities should be considered separately.

- Operation omission (E_0): An operator omits performing a task when following a procedure (one task in a procedure).
- Operation execution omission (E_1): An operator omits performing a sub task when following a task. (one sub task in a task).
- Wrong screen selection (E_{2SS}): An operator selects a wrong screen when performing a task.
- Wrong device selection (E_{2DS}): An operator selects a wrong control device when performing a task.



	Tasks	Possible human error modes							
1	**1. Open PORV block valves**	E0							
2	Press valve 'PV445' button				E2DS				
3	Press 'Manual' button		E1				E4		E6
4	Press the Acknowledge button 'OK'		E1						
5	Press valve 'HV6' button				E2DS				
6	Press 'Open' button		E1			E3			E6
7	Press the Acknowledge button 'OK'		E1						
8	**2. Open Aux FW level control valves**	E0							
9	Press 'Graphic' button			E2SS					
10	Select 'Feed Water System (FWS)'			E2SS					
11	Press valve 'HV313' button				E2DS				
12	Fully open the valve 'HV313'		E1					E5	E6
13	Press the Acknowledge button 'OK'		E1						
14	Press valve 'HV315' button				E2DS				
15	Fully open the valve 'HV315'		E1					E5	E6
16	Press the Acknowledge button 'OK'		E1						
17	**3. Isolate letdown flow form ruptured S/G**	E0							
18	Press set point control valve				E2DS				
19	Press 'Manual' button						E4		E6
20	Regulate controller setpoint of ruptured S/G PORV to 79.1 kg/cm^2		E1					E5	E6
21	Press 'Auto' button						E4		E6
22	Press the Acknowledge button 'OK'		E1						
23	**4. Close steam distribution valve which supplies flow to turbine driven**	E0							
24	Press valve 'HV314' button				E2DS				
25	Fully close the valve 'HV314'		E1					E5	E6
26	Press the Acknowledge button 'OK'		E1						
27	**5.Reset SI and AUX FW Actuation Signal**	E0							
28	Press 'Graphic' button			E2SS					
29	Select 'reactivity system'			E2SS					
30	Presss 'safety injection bypass' button				E2DS				
31	Press 'bypass' button		E1						E6
32	Press the Acknowledge button 'OK'		E1						
33	Presss 'safety guard' button				E2DS				
34	Press 'reset' button		E1						E6
35	Press the Acknowledge button 'OK'		E1						

Fig. 4. Possible human error modes according to each soft control task

As a result of these modifications, the possible human errors during the process are classified into eight types by an additional analysis. Execution tasks in Emergency Operating Procedure (EOP) are then analyzed to verify which human error modes may occur for each soft control task, as shown in Fig. 4.

3 Development of a Framework for HRA Method in Consideration of Soft Control

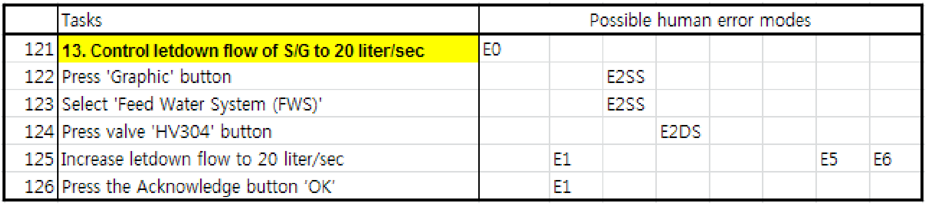
3.1 Secondary Tasks

In the new operation environment of Advanced MCRs, the operation actions of operators are divided into primary tasks (e.g., providing control inputs to plant systems) and secondary tasks (e.g., manipulating the user interface to access information or controls or to change control modes). Interface management tasks are referred to as secondary tasks because they are concerned with controlling the interface rather than the plant [11].

3.2 Sequential Behavior for Unit Task Completion

As explained in the task analysis of soft control, each subtask is included in one of four sub steps: operation selection, screen selection, control device selection, and operation execution. In other words, the operator should follow the subtasks sequentially to complete one unit task according to four sub steps. If the operator fails to perform subtasks at any steps, the operator should recover the failure tasks and then continues to perform the next subtasks. For example, there is one unit task 'Control letdown flow of S/G to 20 liter/sec', as shown in Fig. 5.

In order to complete this unit task, the operator first should succeed in pressing the 'Graphic' button, which is one of the navigation tasks (secondary tasks). Next, the operator also should select 'Feedwater system' to find control device 'HV304' (secondary task). The operator then increases the letdown flow to 20 liter/sec and finally pushes the 'OK' button to send a signal to the control device. If the operator fails to perform any subtasks, failure subtasks should be recovered to continue performing the next subtask.



	Tasks	Possible human error modes							
121	**13. Control letdown flow of S/G to 20 liter/sec**	E0							
122	Press 'Graphic' button			E2SS					
123	Select 'Feed Water System (FWS)'			E2SS					
124	Press valve 'HV304' button				E2DS				
125	Increase letdown flow to 20 liter/sec		E1					E5	E6
126	Press the Acknowledge button 'OK'		E1						

Fig. 5. Example of task including sub tasks

3.3 Dependency among Subtasks

As shown in Fig. 4 and Fig. 5, given unit tasks contain different numbers of subtasks. Due to sequential behavior for unit task completion, failure or success of one subtask may affect failure or success of the next subtask if two subtasks are not mutually independent.

By adopting the dependency model from THERP [2], failure or success probabilities of unit tasks including subtasks can be estimated reasonably. However, determination of the level of dependency should be differently developed in our model by considering characteristics of new HSI and soft control.

Level of Dependence. The approach taken in the THERP handbook is to reduce the positive continuum of conditional probability to a small number of discrete points. THERP use five points: the two end points of zero dependence (ZD) and complete dependence (CD) plus three points in between. These intermediate points are called low dependence (LD), moderate dependence (MD), and high dependence (HD) [2].

Determination of Level of Dependence in Advanced MCRs. Determination of the level of dependency should be differently developed in our model by considering characteristics of new HSI and soft control.

The THERP approach to dependency assessment uses several parameters to determine the level of dependency between events, including same or different crew, time, location, and cues. Accompanying these parameters is a scale that rates dependency from zero (no dependency) to a value representing complete dependency [2].

However, several parameters defined in THERP should be modified considering the new features of advanced MCRs. Since soft controls are control devices having connections with control and display systems that are mediated by software rather than direct physical connections and their functions may be variable and context dependent rather than statically defined, location is not important when determining level of dependency.

NUREG/CR-6635 points out several causes of soft control human error that are possibly related to parameters for dependency level [10]:

- Description error: the similarity of an object, and the amount of separation between them, especially those presented via a graphical user interface.
- Misordering the component of an action sequence: reversed and repeated steps.
- Loss of activation errors: keyhole effect (the HSI may only have space for a few displays at one time).

From the survey conducted for NUREG/CR-6635, similarity of control devices and their tags in flat display panels and repetition tasks should be added as parameters to determine the level of dependency. Soft control has an additional unique characteristic known as group control. Group control refers to when the operator is able to control devices as a group.

After analysis of the feature of soft control, determination of the level of dependency for soft control is developed using a decision tree, as shown in Fig. 6. And conditional probabilities according to dependency levels are shown in Table 1.

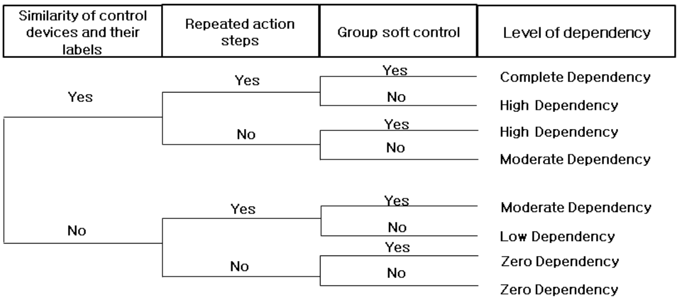


Fig. 6. Decision tree for level of dependency

Table 1. Conditional probabilities acccording to dependency levels

Dependency level	Equation for P(B)
Complete	1.0
High	[1+P(A)]/2
Moderate	[1+6P(A)]/7
Low	[1+19P(A)]/20
Zero	P(B)

3.4 A Framework for HRA Method in Consideration of Soft Control

As explained in sections 3.1 to 3.3, a framework for a HRA method under consideration of soft control is developed using concepts of secondary tasks, sequential behavior for unit completion, and dependency among subtasks. In our model, a success path (a path where all subtasks succeed) is considered to calculate soft control execution human error probability (HEP) with consideration of dependency among tasks.

Concept of HEP Calculation. The success probability of each subtask depends on the human error probabilities according to human error modes classified in Fig. 4 and 5, and their recovery failure probabilities. Recovery failure probabilities according to human error modes are expressed as R_i. In other words, R_i equals the recovery failure probability of E_i (i=0, 1, 2SS, 2DS, 3, 4, 5, 6). The probability that the operator succeeds in each subtask for unit tasks 1 and 2 is then expressed in Tables 2 and 3, respectively.

Table 2. Success probability of each sub tasks for one unit task 1

Each task	Possible human error modes	Success probability
Control letdown flow of S/G to 20 liter/sec	E_0	1- E_0R_0
Press 'Graphic' button	E_{2SS}	1- $E_{2SS}R_{2SS}$
Select 'Feedwater system (FWS)'	E_{2SS}	1- $E_{2SS}R_{2SS}$
Press valve 'HV304' button	E_{2DS}	1- $E_{2DS}R_{2DS}$
Increase letdown flow to 20 liter/sec	E_1 or E_5 or E_6	1- $(E_1R_1+E_5R_5+E_6R_6)$
Press the Acknowledge button 'OK'	E_1	1- E_1R_1

Table 3. Success probability of each sub tasks for one unit task 2

Each task	Possible human error modes	Success probability
Open Aux FW level control valves	E_0	1- E_0R_0
Press 'Graphic' button	E_{2SS}	1- $E_{2SS}R_{2SS}$
Select 'Feed Water System (FWS)'	E_{2SS}	1- $E_{2SS}R_{2SS}$
Press valve 'HV313' button	E_{2DS}	1- $E_{2DS}R_{2DS}$
Fully open the valve 'HV313'	E_1 or E_5 or E_6	1- $(E_1R_1+E_5R_5+E_6R_6)$
Press the Acknowledge button 'OK'	E_1	1- E_1R_1
Press valve 'HV315' button	E_{2DS}	1- $E_{2DS}R_{2DS}$
Fully open the valve 'HV315'	E_1 or E_5 or E_6	1- $(E_1R_1+E_5R_5+E_6R_6)$
Press the Acknowledge button 'OK'	E_1	1- E_1R_1

If there is no dependency (zero dependency) among the subtasks, it is easy to calculate the HEP of two unit tasks (Human Error Probability of unit task 1, HEP_1 and Human Error Probability of unit task 2, HEP_2)

$$\begin{aligned} HEP_1 = 1 - \{&(1 - R_0E_0) \times (1 - R_{2SS}E_{2SS}) \times (1 - R_{2SS}E_{2SS}) \\ &\times (1 - R_{2DS}E_{2DS}) \times (1 - (R_1E_1 + R_5E_5 + R_6E_6)) \times (1 - R_1E_1)\} \end{aligned}$$

$$\begin{aligned} HEP_2 = 1 - \{&(1 - R_0E_0) \times (1 - R_{2SS}E_{2SS}) \times (1 - R_{2SS}E_{2SS}) \times (1 - R_{2DS}E_{2DS}) \\ &\times (1 - (R_1E_1 + R_5E_5 + R_6E_6)) \times (1 - R_1E_1) \times (1 - R_{2DS}E_{2DS}) \\ &\times (1 - (R_1E_1 + R_5E_5 + R_6E_6)) \times (1 - R_1E_1)\} \end{aligned}$$

where E_i=human error probabilities for each human error mode and R_i=recovery failure probabilities. However, if dependency among subtasks exits, the HEP calculation should be modified considering the level of dependency among subtasks using a decision tree for the dependency level.

The HEP of two unit tasks can then be calculated by applying the dependency level.

In the case of HEP_1, there is no dependency (ZD) among subtasks. Then,

$$\begin{aligned} HEP_1 &= 1 - \{(1 - R_0E_0) \times (1 - R_{2SS}E_{2SS}) \times (1 - R_{2SS}E_{2SS}) \\ &\quad \times (1 - R_{2DS}E_{2DS}) \times (1 - (R_1E_1 + R_5E_5 + R_6E_6)) \times (1 - R_1E_1)\} \end{aligned}$$

In the case of HEP_2, there is high dependency between subtasks 'Press valve 'HV313' button to Press the Acknowledge button 'OK'' and 'Press valve 'HV315' button to Press the Acknowledge button 'OK''.

Then,

$$\begin{aligned} HEP_2 &= 1 - \{(1 - R_0E_0) \times (1 - R_{2SS}E_{2SS}) \times (1 - R_{2SS}E_{2SS}) \\ &\quad \times (1 - R_{2DS}E_{2DS}) \times (1 - (R_1E_1 + R_5E_5 + R_6E_6)) \times (1 - R_1E_1) \\ &\quad \times \frac{1+(1-R_{2DS}E_{2DS})}{2} \times \frac{1+(1-(R_1E_1+R_5E_5+R_6E_6))}{2} \times \frac{[1+(1-R_1E_1)]}{2}\} \end{aligned}$$

Using the calculated HEP, the HEP calculation equation is generalized as follows.

$$HEP = 1 - \left\{(1 - R_0E_0) \prod \frac{1 + K\,(1 - \sum_{i \neq 0} R_iE_i)}{1 + K}\right\} \quad (1)$$

where,
E_i = human error probabilities at human error mode i
R_i = recovery failure probabilities at human error mode i.
i = 1, 2SS, 2DS, 3, 4, 5, and 6 according to human error modes.
K=19, 6, 1, 0 depending on the dependency level

4 HEP Estimation Using Developed HRA Method

4.1 Nominal HEP Database According to Human Error Mode for Advanced MCRS Using Soft Control

Since the developed method is significantly dependent on nominal HEPs according to human error modes such as E_0, E_1, E_{2SS}, E_{2DS}, E_3, E_4, E_5, and E_6, a nominal HEP database such as a THERP table should be developed in advance. Although THERP tables are well organized, their nominal HEPs are not specific for advanced MCRs.

In a related study by the authors, nominal HEPs according to human error modes were developed by experiments using a mockup simulator for an advanced MCR [13].

Additional experiments performed by the same procedures as used in the previous experiments were performed to update the nominal HEP database. However, nominal HEPs according to human error modes should be modified for direct input of the developed HRA method. The results of this empirical study could not explain E_0 because no human error occurred. Moreover, E_{2SS} and E_{2DS} are derived as E_2. Nominal HEPs according to human error modes are modified by analyzing human error checklists for E_{2SS} and E_{2DS} and by using an assumption for E_0, as shown in Table 4.

Table 4. Modified nominal HEP according to human error modes

Human error modes	Nominal HEP	Human error modes	Modified nominal HEP
		E_0	*5.00E-3 (Assumption)*
E_1	4.63E-3	*E_1*	*4.63E-3*
E_2	7.85E-3	*E_{2SS}*	*5.23E-3(2/3 of E_2)*
		E_{2DS}	*2.62E-3(1/3 of E_2)*
E_3	7.25E-3	*E_3*	*7.25E-3*
E_4	6.52E-2	*E_4*	*6.52E-2*
E_5	2.35E-2	*E_5*	*2.35E-2*
E_6	7.25E-3	*E_6*	*7.25E-3*

4.2 Recovery Failure Probabilities

Recovery failure probabilities in this study are assumed using the recovery failure tree from K-HRA [3] and insight from performed experiments. In case of recovery failure probability of secondary tasks such as screen navigation tasks and control device selection tasks, it is assumed that the recovery failure probabilities are assigned as 0.01, since most screen navigation tasks are recovered in the performed experiments.

Three cases of recovery failure probabilities for HEP calculation are then selected, as shown in Table 5.

Table 5. Recovery failure probabilities

Case	R_0	R_1	R_{2SS}	R_{2DS}	R_5	R_6
Case 1	0.03	0.03	0.01	0.01	0.03	0.03
Case 2	0.05	0.05	0.01	0.01	0.05	0.05
Case 3	0.15	0.15	0.01	0.01	0.15	0.15

4.3 HEP Estimation

Based on the suggested HEP calculation method with the developed database including nominal HEPs in Table 4, recovery failure probabilities in Table 5 according to human error modes, and the dependency model, HEPs of two different unit tasks shown in Tables 2 and 3, respectively, are estimated.

Table 6. Result of HEP_1 and HEP_2 based on nominal HEPs, dependency level according to three cases recovery failure probabilities

Case	HEP_1	HEP_2
Case 1	1.48E-03	2.09E-03
Case 2	2.38E-03	3.39E-03
Case 3	6.87E-03	9.87E-03

In other words, once levels of dependency for each subtask are determined, input values from the database are inserted to the equation of HEP estimation. From the results of HEP_1 and HEP_2 based on nominal HEPs, dependency levels according to three cases of recovery failure probabilities are shown in Table 6.

5 Summary and Conclusion

This paper proposed a new framework for a HRA method for evaluation of soft control execution human error in advanced MCRs, because many HRA methods do not sufficiently consider the features of advanced MCRs such as soft control execution human errors due to the different interfaces between soft control and hardwired conventional type control.

In order to develop the new framework for the HRA method, a soft control task analysis was performed to identify human error modes. From the results of the soft control task analysis, the possible human errors during the process were classified into eight types. It was also identified that the operator should follow the subtasks sequentially to complete one unit task, and if the operator fails to perform subtasks, the operator should recover the failure tasks. Moreover, dependency among subtasks is considered by modifying the determination of levels of dependency in the THERP model. This modification is performed according to several causes of soft control human error pointed out in NUREG/CR-6635 that may be related to parameters for dependency level.

In our model, a success path is considered to calculate soft control execution HEP with consideration of dependency between two subtasks. By deriving two examples of HEP equations for representative soft control unit tasks in consideration of secondary tasks, sequential behavior, and dependency among subtasks, a HEP calculation equation is generalized. A database for inputs to the general HEP equation such as nominal HEPs and recovery failure probabilities is developed and applied to estimate HEPs. Finally, HEPs are estimated using the developed nominal HEPs by assuming three different cases of recovery failure probabilities.

Acknowledgement. This work was supported by Nuclear Research & Development Program of the National Research Foundation of Korea grant, funded by the Korean government, Ministry of Science, ICT & Future Planning (Grant Code: 2012M2A8A4025991) 2014M2A8A4025991).

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