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Original Article

An algorithm for evaluating time-related human reliability using instrumentation cues and procedure cues

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ABSTRACT

The performance time of human operators has been recognized as a key aspect of human reliability in socio-complex systems, including nuclear industries. Because of the importance of the time factor, most existing human reliability assessment methods provide ways to quantify human error probabilities (HEPs) that are associated with the performance time. To quantify such kinds of HEPs, it is crucial to rationally predict the length of time required and time available and compare them. However, there have not been detailed guidelines that identify the critical cue presentation time or initial time of human performance, which is important to calculate the time information. In this paper, we introduce a time-related HEP calculation technique with a decision algorithm that determines the critical cue and its timing. The calculation process is presented with the application examples. It is expected that the proposed algorithm will reduce the variability in the time-related reliability assessment and strengthen the scientific evidence of the assessment process. The detailed description is provided in the technical report KAERI/TR-7607/2019.

1. Introduction

Because it has been revealed that human errors significantly contribute to the incidents or accidents in socio-technical industries, much research has been conducted on the quantitative evaluation of human reliability [1]. Several types of human reliability assessment (HRA) methods have been developed, for example, THERP (Technique for Human Error Rate Prediction) [2], ASEP (Accident Sequence Evaluation Program) [3], ATHEANA (A Technique for Human Event Analysis) [4], SPAR-H (Standardized Plant Analysis Risk - Human Reliability Analysis) [5], HuRECA (Human Reliability Evaluator for Control Room Actions) [6], Petro-HRA [7], CBDT (Cause-Based Decision Tree) [8], and HCR/ORE (Human Cognitive Reliability/Operator Reliability Experiments) [8]. The developed methods have guided safety engineers or system assessors to systematically identify the potential human failure events (HFEs), scrutinize meaningful human responses to those events, and predict the possibility of the event occurrences.

Among the factors affecting human reliability, human performance time can be highly significant depending on the context and the human response because (1) any human response requires time to recognize cues and implement actions and (2) urgent situations might intensify the complexity of the human tasks [7]. Most HRA methods have thus included a process to appraise time factors during the quantification of a human error probability (HEP) for a given HFE. The next section will summarize the approaches for quantifying time-related HEPs.

To quantify the time-related reliability, the HRA practitioners generally (1) compare the time required to complete the goals of the given tasks and the time available to maintain the system safety or (2) calculate the time margin between the time required and the time available. Fig. 1 shows an example of the timeline regarding a proceduralized response of a human operator. When an operator recognizes a cue from a plant instrumentation, she or he searches a proper procedure for the symptom, follows the instructions described in the found procedure, and implements an action provided in the procedure. The time needed to perform these human actions is the time required. On the other hand, if the operator has to finish the given event within a temporal success criterion or allowed time, the period from the initial time to the criterion, which is the time available, should also be calculated. Based on the estimated information about the time required and the time

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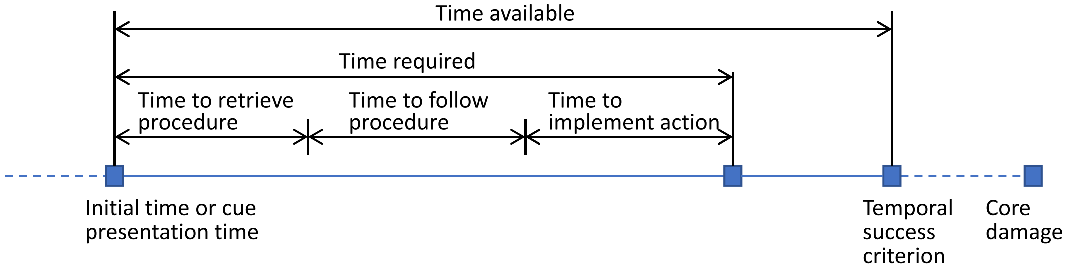

Fig. 1. A timeline example of human responses in proceduralized events.

available, the HRA practitioners can determine time-based HEPs or evaluate a level of the time availability factor in the event.

In spite of the importance of time information, an explicit guideline on determining the lengths of time required and time available has not been yet developed in HRA practice. The cues of human response are usually defined based on the procedures or plant indicators. Hence, the cue presentation times are determined by predicting when operators can reach a significant procedural step or when a plant's information can be annunciated by the instrumentations. However, in the case of human events that are carried out from multiple cues, it is difficult to decide which critical cue is significant to the reliability among them. For example, suppose an arbitrary example that a feed-and-bleed operation is required owing to the depletion of an auxiliary feedwater storage tank (AFWST) (Table 1). The earliest this operation can be initiated is when a low-level alarm in the storage tank presents. However, because by plant procedures the crew is directed to open the pilot operated safety relief valve (POSRV) after the spring-loaded pilot valve in the POSRV is opened by the high pressure of the reactor control system, the operator should wait until the pilot valve opens on high pressure. In this situation, it is unclear which point could be the critical cue and which time could be the initial time, such as the time the spring-loaded pilot valve was open, the time the tank level was low, and the time the reactor was tripped. Due to this kind of ambiguity, assessing human reliability can vary, and the credibility of the HRA results can decline.

In this paper, we introduce an algorithm that determines information of the human performance time to quantify an HEP. It is assumed that the temporal success criterion is assessed via engineering judgments or thermal-hydraulic analyses during an HFE definition process. This technique compares the procedure cue time (PCT) and instrumentation cue time (ICT) to calculate the time required and time available based on statistical practice. This technique was developed for the EMBRACE (EMpirical data-Based crew Reliability Assessment and Cognitive Error analysis) method [9], but it is believed that this technique can also be applied to other kinds of HRA methods.

2. Time-based reliability in the existing HRA methods

In this section, to understand the state-of-the-art HRA practices regarding the performance time, the existing HRA methods were briefly reviewed. More comprehensive surveys of HRA methods could be found in Ref. [1,10]. The concept of performance time is recognized and used differently for the HEP quantification depending on the HRA method. The THERP method provides a time-reliability curve (Fig. 2, left) that quantifies a failure probability of cognitive or diagnostic action [2]. This model is also employed in the ASEP [3], K-HRA [11], and HuRECA [6] methods. The time margin is calculated by subtracting the time for perceiving a cue and the time needed to execute an action from the temporal success criterion. Based on the absolute value of the time margin, the diagnosis HEP is estimated. On the other hand, the HCR/ORE [8] and CBDT [8] methods in the EPRI (Electric Power Research Institute) HRA calculator are also available to predict cognitive HEPs. The CBDT method assesses the failure mechanisms in the interactions of crews with procedures and plant instrumentations to quantify the cognitive HEP considering the PSF effects, except for the timing issue. However, the HCR/ORE deals with the non-response probability in association with the performance time for an HFE. The HCR/ORE method generates a probability by using a ratio between the cognition time and the time available based on the cumulative lognormal distribution equation (Fig. 2, right) [8]. In this method, the cognition time and time available should be decided based on the time of cue occurrence.

Many other HRA methods such as HEART [12] (Human Error Assessment and Reduction Technique), CREAM [13] (Cognitive Reliability and Error Analysis Method), SLIM [14] (Success Likelihood Index Method), SPAR-H [5], and Petro-HRA [7] consider time as one of the significant performance shaping factors (PSFs). For example, the SPAR-H method evaluates the factor of an available time for a diagnosis HEP by selecting one among five possible states: Inadequate time, barely adequate time, nominal time, extra time, and expansive time. If the available time is inadequate, the diagnosis HEP is calculated to be 1.0. If the available time is barely adequate, the nominal HEP (i.e., 0.01) for diagnosis is multiplied by 10. The definitions of each state and the following PSF multiplier are summarized in Table 2 [15]:

In the Petro-HRA guidelines, which were developed based on the SPAR-H method, significant challenges and recommendations for extracting the time information are described [7]. For example, it is recommended to analyze and visualize the timeline of the event progressions and human actions. Some good practices for deriving meaningful information about the time required are also

Table 1
Time information for a feed-and-bleed operation (FRP: functional recovery procedure).

Cue or Execution	Procedure cue	Instrumental cue time (min)	Execution time (min)
Verify AFWST was exhausted	Periodic check of safety functions	1380	0
Verify spring-loaded pilot valves were opened	FRP-06, step 102	1782	0
Supply power of POSRVs	FRP-06, step 107	–	5
Open POSRVs	FRP-06, step 109	–	1

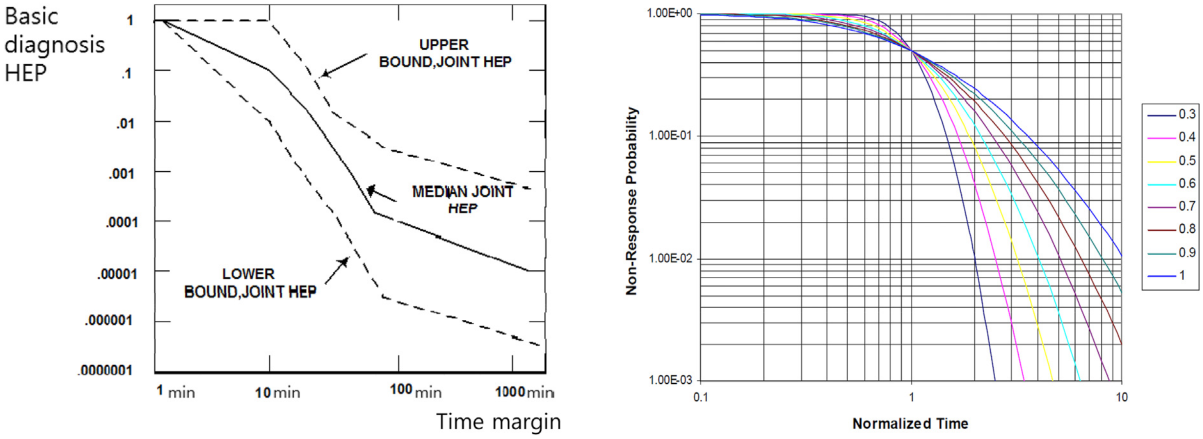

Fig. 2. Time-reliability curve of THERP [2] (left) and HCR/ORE [9] (right) methods.

Table 2
States and multipliers of available time to diagnose HEP in SPAR-H [15].

Available time states	Description	Multiplier
Inadequate time	The time required is higher than the time available, i.e., the time margin is negative.	HEP = 1.0
Barely adequate time	The time required is equal to the time available, i.e., the time margin is zero.	10
Nominal time	The time required is slightly less than the time available; a minor margin exists.	1
Extra time	The time required is considerably less than the time available. The time margin is hence larger than zero, but smaller than the time required.	0.1
Expansive time	The time available is much higher than the time required. The time margin is also higher than the time required.	0.01

presented. These include checking the uncertainties of time estimates, avoiding biases in the input data, taking triangular perspectives during information conflicts, controlling unrealistic optimism, considering situational factors, and applying average performances. The considerations that exist during the analysis process of the time available for petroleum industries were also introduced with the possible approaches to identify the time available.

Although the abovementioned methods emphasize that the time-related reliability is calculated using the time required and time available, the process of defining such time information has been made by the analysts subjectively. Intuitively, it can be said that the time required starts from the time the cue is presented. However, if the cue occurs within a short period of time after the reactor trip, how the operator responds to the initial emergency situation can affect the entire performance time of the human actions. In this case, the time required needs to be considered from the reactor trip time. On the other hand, some long-term operations may not be significantly associated with any action that was performed a long time ago. The time required and available for those operations can be counted from the time the relevant cue occurs. However, because no clear criterion has been established, the high variability of HRA results exists among the analysts, and model uncertainties that are not negligible remain in the HRA applications.

3. Proposed method

3.1. Assumption

To resolve the ambiguity issues in determining the time required and time available, the following assumptions were considered. First, the human performance time, including the cognition and execution actions required for a given event, can be described with a specific statistical distribution. For example, the empirical study of APR1400 crews has shown that the time to carry out tasks described in the procedures can be represented by a log-normal distribution [9]. Second, the crews are expected to initiate their tasks only when the cues appear. It can be observed in reality that some operators can proactively respond to some sort of situation. However, because it is not always ensured that the proactive responses are safe and the proactive behaviors are not generally allowed in many countries due to the conduct of operations, they are not considered for the time calculations. Third, all tasks to be performed for a given HFE should be proceduralized. In the case of skill-of-the-crafts, which means well-practiced actions, but unwritten in procedures, it is possible to represent them with a set of procedural tasks. However, if the tasks are not provided in any procedure nor are they practiced, we cannot expect that the human actions are credible. Fourth, it is presumed that two kinds of information are available for each cue: Instrumentation cue (e.g., alarm, indicator, plant parameter, etc.) and procedure cue (e.g., emergency operating procedure, abnormal operating procedure, etc.). Some instrumentation cues are provided with other cues at the initial situation of events. In addition, some procedure sentences just require simple decisions and instructions without any comparison between the plant parameters and procedural conditions. For those cases, it can be thought that the instrumentation cues are not present. However, in most cases, because the instrumentation cues can evoke the necessity of procedures or provide information to be matched with the procedural conditions, they are essential for reliability assessment. Fifth, all cues of an HFE are equally important to initiate the given tasks in this method. In other words, each cue should be perceived by the operators before the progression of the relevant procedural steps or executions. Lastly, the proposed technique can be employed to evaluate the level of temporal urgency or to directly calculate the failure probability of timely performance. Some HRA methods predict an HEP of cognitive behavior based on time variables. However, this technique only deals with whether the time available is sufficient for performing the required human actions. The cognitive action reliability, including the omission or commission of tasks and their recoveries, is not considered in this algorithm. It is also viewed that the action after the temporal success criterion does not affect the time-related reliability. Hence, the recoverability of the failure due to insufficient time is not included in this technique.

3.2. Developed algorithm

Based on the assumptions of this technique, it can be thought that the crews basically compare the plant information with the instructions written in the procedures in order to control the system according to the procedures. Therefore, it is important to identify the procedural cue time (PCT) and instrumentation cue time (ICT). While the PCT information can be estimated from the simulation records of operators, walk-though analyses, or interviews with experienced staff, the ICT can be predicted via thermal-hydraulic analyses or engineering judgments. For instance, if the PCT and ICT information described in Table 1 is obtained, the timeline of the feed-and-bleed operation can be illustrated, as shown in Fig. 3. The orange rhombuses indicate when the operators have reached particular procedure steps. The blue squares are the appearance times of significant instrumentation information. The temporal success criterion was 1872 min after the reactor trip.

From Fig. 3, it can be seen that there are two big gaps between the PCTs and related ICTs. For example, a low-level AFWST alarm occurs 1380 min after the plant is shut down, while the operators can reach the associated procedural step 24 min after the trip. In addition, within 18 min after the tank is exhausted, the operator can arrive at the procedure sentence to verify that the spring-loaded pilot valve is open, but the valve actually opens 402 min after the depletion of the tank. In this situation, the following issues should be included in calculating the time required and time available. First, the crew activities performed before the instrumentation cue presence (e.g., the low-level alarm and spring-loaded pilot valve open) does not significantly influence the entire time-related reliability. Second, the operators have to take some time to retrieve the procedural step. Because the crews have read the relevant sentence long before they got the plant information, they are probably not ready to instantly proceed to the procedural step.

Fig. 4 shows the flow chart of the developed algorithm to calculate the time-related HEP using the information of PCTs and ICTs. There are multiple cues indexed by *i*, and each cue contains both a procedural cue and instrumentation cue. Basically, this technique compares the difference between the period from the initial time to the PCT and the period from the initial time to the ICT and takes the higher period as the human performance completion time (HPCT). In this figure, it can also be found that (1) the HPCT additionally involves the procedure retrieval time (PRT), and (2) the ICT (i) is regarded as a new initial time when the period from the initial time to ICT (i) is significantly larger than the period from the initial time to PCT (i). In this algorithm, the criterion determining the significant difference is defined as the 95th percentile of the expected previous action time, which is similar to the process of the statistical mean-difference test. In other words, if the period from the initial time to ICT (i) is longer than the 95th percentile of the period from the initial time to PCT (i), it can be declared that this cue is critical for estimating the time required and time available. If the performance time generally follows a lognormal distribution, which can be expressed by Lognormal (μ, σ), this measure can be described by Eq. (1). Because the value of 1.645 implies the standard score for the 95th percentile of the standard normal distribution, the exponentiated 1.645 multiplied by the sigma indicates the 95th percentile of the period between the PCT (i) and the initial time.

$$(ICT\text{ - }InitialTime) > (PCT\text{ - }InitialTime)\cdot\exp(1.645\cdot\sigma) \tag{1}$$

The algorithm can also be described with a pseudo-code that can be implemented into the software. In Fig. 5, *PC* stands for a procedural cue.

4. Case study

This section verifies the feasibility of the proposed method with three case studies. In this study, the HEP regarding the human performance time is predicted based on the developed algorithm. To calculate a time-related HEP, we used a lognormal model of Eq. (2), which is employed in the HCR/ORE [8] and EMBRACE [9] methods. The minimum HEP is assumed to be 1.0E-6 [15].

$$HEP = 1 - \Phi\left[\frac{\ln(Tavail/Treq)}{\sigma}\right]. \tag{2}$$

here, Φ is the cumulative distribution of the standard normal distribution, and *Tavail* and *Treq* represent the time available and time required, respectively.

For this analysis, we assumed the values of the parameters or the performance times of procedure segments, as shown in Table 3. A PCT for a cue is computed by combining multiple time values for the procedure segments. The emergency operating procedures employed in APR1400 were assumed for this study. Specifically, the operators initially followed the standard post-trip action (SPTA) procedure when the plant is tripped. After the SPTA, they identify the accident situation using the diagnostic action (DA) procedure. An optimal recovery procedure (ORP) or FRP corresponding to the accident is then selected and followed. The crew also monitors the safety-critical functions periodically. If any safety criterion is not satisfied, they enter the FRP.

The index numbers of procedural steps in this study were arbitrarily assumed in this study for concretely explaining the cases.

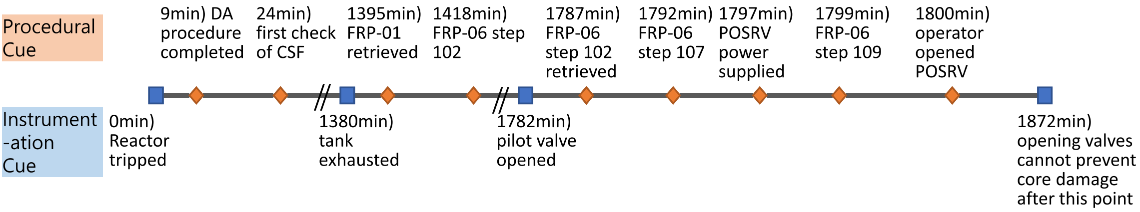

Fig. 3. Timeline of Table 1 (CSF: critical safety function; DA: diagnostic procedure).

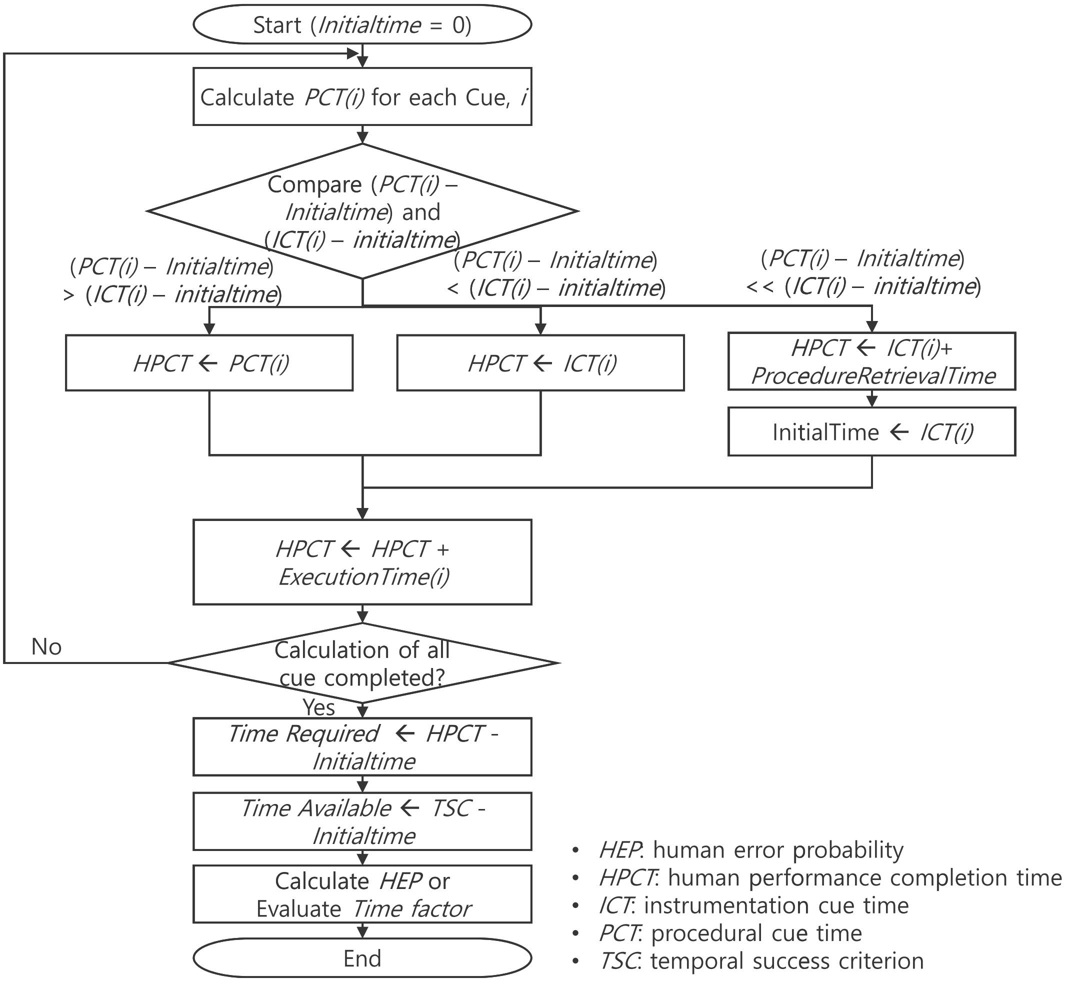

Fig. 4. Algorithm calculating a time-related HEP using PCTs and ICTs.

```
PROGRAM HEP:
 InitialTime ← 0
 HPCT ← InitialTime
 PC_0 ← “ReactorTrip”
 REPEAT with i=1 to NumberOfCues
  PCT_i ← HPCT + CalaulteProcedureFollowingTime(PC_i-1, PC_i)
  HPCT ← MAX (PCT_i , ICT_i )
  IF (ICT_i - InitialTime) > NinetyFifthPercentile(PCT_i - InitialTime) THEN
  //This ICT is the basis of time-reliability
   InitialTime ← ICT_i
   HPCT ← HPCT + ProcedureRetrievalTime
  END IF
  HPCT ← HPCT + ExecutionTime_i
 END REPEAT
 TimeRequired ← HPCT - InitialTime
 TimeAvailable ← TemporalSuccessCriterion - InitialTime
 Return CumulativeDistributionFunction (TimeRequired, TimeAvailable, StatisticalParameter)
END HEP
```

Fig. 5. Pseudo-code for the proposed algorithm.

4.1. The event of starting a startup feedwater pump

This event requires a human operator to start a start-up feedwater pump when all other feedwater pumps are unavailable. In order for this event to be successful, the operator should (1) recognize that the feedwater flow is low and (2) start the startup pump. The associated plant information is provided within 1 min after the reactor trip, and the temporal success criterion is 45 min. The operator’s responses are provided in the 6th step of an ORP. Based on the assumed estimates, the timeline diagram can be

Table 3
Time parameters assumed for this case study [9].

Parameter/time information	Values assumed
Sigma (σ) of the lognormal model	0.3403
The interval from reactor trip to the beginning of the SPTA procedure	0.6 min
The performance time of a single step in SPTA procedure	0.5 min
The interval from reactor trip to diagnosis completion	9 min
The performance time of unit step in ORP	0.7 min
The performance time of unit step in FRP	1 min
The performance time of strategy selection for FRP	15 min
The discussion time for procedure transition or overall status identification	0 min
The retrieval time of a procedural step that progressed	5 min
The period for safety function status check	Every 15 min

depicted as shown in Fig. 6.

In this event, because the ICT is not longer than the PCT, the time required needs to contain the interval of all human performances after the reactor trip. Therefore, the time required is 14.2 min while the time available is 45 min. Using Eq. (2) and the sigma estimate, the time-related HEP is 3.50E-4.

4.2. The event of actuating a safety injection signal

This human event has to manually actuate a safety injection signal when the signal is not automatically generated. The initiating event is a medium-size break in a reactor coolant system. To successfully carry out this mission, the operator should (1) recognize the failure of the automatic generation of the signal and (2) press the two push-buttons for its manual generation. The associated plant information is available 0.217 min after the reactor trip, and the temporal success criterion for this event is 4.05 min. The manual actuation is described in the 4th step of the SPTA procedure. Based on this information and the assumed parameters, the timeline diagram of this event is illustrated as shown in Fig. 7.

Similar to the previous event case, the time required for this event also needs to involve the interval from the initial emergency situation to the end of manual actuation. Therefore, the time required is 3.6 min. Because the ICT is not higher than the PCT, the time available is 4.05 min. Using Eq. (2) and the sigma estimate, the time-related HEP is 3.65E-1.

4.3. The event of feed-and-bleed operation by depletion of AFWST

This event is the example event described in Table 1. The crew has to manually open POSRVs when the secondary heat removal is not available due to the low AFWST level. To successfully fulfill the goal, the operator should verify both the low level of AFWST and the opened pilot valves of the pressurizer. After the spring-loaded pilot valves are opened, the crew has to supply the power of the POSRVs and fully open them. The associated plant information and procedural steps are provided in Table 2, and the temporal success criterion is 1872 min. Fig. 3 shows the timeline diagram of this event based on the assumed estimates.

In this event, it is interesting that there are temporal gaps between the ICTs and PCTs regarding the verification of the AFWST level and spring-loaded pilot valves. The ICT regarding the AFWST depletion is significantly higher than the PCT from the time of the reactor trip (the period between ICT and reactor trip time: 1380 min; the 95th percentile of the period from reactor trip time to PCT: 24 × exp (1.645 × 0.3403) min). In addition, the period to the ICT for the opened pilot valve is higher than the 95th percentile of PCT from the tank depletion (ICT: 1782-1380 min; the 95th percentile of PCT: (1418−1380) * exp (1.645 × 0.3403) min). Therefore, the opening time of the pilot valve (1782 min) is regarded as the initial time of this event. The time required is 18 min (=1800-1782 min), and the time available is 90 min (=1872-1782 min). Using Eq. (2) and the sigma estimate, the time-related HEP is 1.13E-6.

4.4. Comparison of HEPs in different critical cues

To understand the effects of the initial time selection, the HEPs where different critical cues are selected are compared. Table 4 compares the time required, time available, and the resultant HEPs using Eq. (2) in the cases where the initial time is (1) the reactor trip time, (2) the last PCT, and (3) the time that the developed algorithm determines. The three events in the above case studies were compared. For the first and second events, the initial time, time required, and time available when the critical cue was the reactor trip were same as the time values when the algorithm selected the critical cue. This is because the algorithm determined the reactor trip time as the initial time. However, for the third event, the HEPs were significantly different according to the selection of critical cues. Generally, the HEPs were relatively low when the last cue of each event was selected, and the HEPs were relatively high when the first cue (i.e., the reactor trip in this study) of each event was chosen. According to the selection of the initial time, the HEPs were drastically different.

This comparison reveals that which cue time is specified as the initial time and which cue is viewed as the critical cue are very significant in estimating the time-related HEP. Therefore, it is recommended to reasonably select the critical cue for a realistic HEP

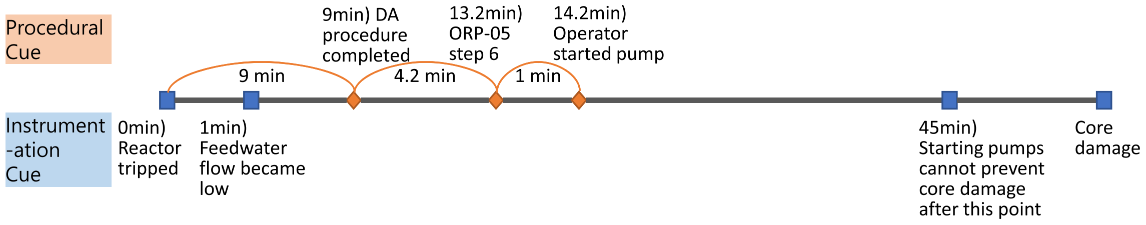

Fig. 6. Timeline diagram of the startup feedwater pump event.

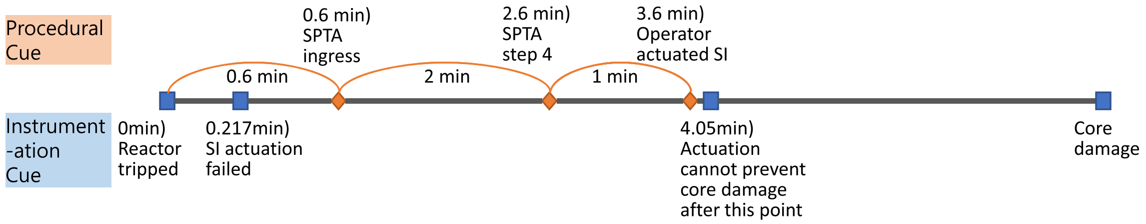

Fig. 7. Timeline diagram of manual actuation of a safety injection signal.

Table 4
Comparison of time-related HEPs modeling different critical cues.

Event		Starting a startup feedwater pump	Actuating a safety injection signal	Feed-and-bleed operation by depletion of AFWST
Critical cue: reactor trip	Initial time (min)	0	0	0
	Treq (min)	14.2	3.6	1800
	Tavail (min)	45	4.05	1872
	HEP	3.50E-04	3.65E-01	4.54E-01
Critical cue: last procedural cue	Initial time	13.2	2.6	1799
	Treq	1	1	1
	Tavail	31.8	1.45	73
	HEP	0.00E+00	1.37E-01	0.00E+00
This algorithm	Initial time	0	0	1782
	Treq	14.2	3.6	18
	Tavail	45	4.05	90
	HEP	3.50E-04	3.65E-01	1.13E-06

estimation. This algorithm provides a rationale for establishing a critical cue based on the concept of the confidence interval in statistics.

5. Discussion and conclusion

In this study, we propose an algorithm based on statistical theory to calculate the time required and time available. It is believed that this method can relieve the ambiguity in evaluating the human performance time and strengthen the consistency in the assessment. This algorithm can be realized in software to facilitate automatic quantification of time-related reliability. The proposed technique can be used to assess a PSF level regarding temporal sufficiency in some HRA methods (e.g., SPAR-H and an extended version of CREAM) or directly quantify a non-response probability due to insufficient time, as used in the HCR/ORE method. It is noteworthy that the time reliability curve in the THERP method, which surrogates a diagnosis HEP with a time margin, has a different meaning from the HEP in this case study. This is because the reliability regarding diagnosis failures due to cognitive error mechanisms is not covered in this algorithm.

In order to realistically evaluate the time information, the following issues should be considered. First, the accurate identification of the PCT and ICT information is very important. The cue in terms of the time-related reliability implies the information given from instrumentations or procedures that evokes the need for a specific task of the operator. This cue should be clearly defined with consideration of the characteristics of the accident scenarios, procedures, and human-machine-interfaces. The guidance provided in the Petro-HRA method and the control room abandonment analysis showed a useful source for this analysis [7,20]. For example, the time-line analysis with visual representations enhances the clearness of the time information. It is also beneficial to understand the complex relationships between the accident progression, plant responses, and human actions. Second, numeric data from credible sources such as simulations, interviews, walk-downs, expert elicitations, event reports, and thermal-hydraulic analysis should be appropriately extracted to estimate the procedure progression time or execution time. There have been several activities that used the simulation-based data collection [16,17]. The use of these data is expected to improve the quality of the analysis. Lastly, it is important to consider the effect of PSFs on the performance time. Lois et al. [18] and Park et al. [19] performed some empirical studies; however, it is still necessary to investigate the relation between the PSFs and performance time.

There are some issues to be discussed regarding some assumptions employed in the case study. First, the retrieval time or recognition time for an instrumentation cue was not addressed in this study. Basically, it was assumed that the crews instantly recognize the instrumentation time. If it is necessary to consider an additional retrieval time for instrumentation cues, a delayed time for the retrieval can be inputted in the algorithm instead of the existing presentation time of the instrumentation cue. Second, the discussion time for a significant action such as a procedure transition and overall status identification was not considered in this study. This was because from the simulation observations, it was found that the average performance time in general steps was not significantly different from the average time of the steps for group discussions. If the simulation environments or procedures require a different time for step progressions, it is recommended to calculate the PCT by aggregating each step's performance time rather than multiplying the average performance time of the unit steps with the number of steps performed.

The uncertainty analysis is an important aspect of HRA for risk-related decision-makings. As described in many studies [21], three kinds of uncertainties can be characterized: Parametric, model, and completeness uncertainties. For example, Kim et al. presented a credible interval of the sigma parameter for the log-normal distribution [9]. This information can be used to predict the parametric uncertainty. In addition, it is possible to conduct sensitivity studies that investigate the impacts of different PCT or ICT values by estimating HEPs under different contexts.

It is believed that the proposed algorithm can be employed to dynamically estimate time-based HEPs under various combinations of accident progressions and crews' response planning [22]. By adjusting the ICTs and PCTs that could be predicted differently by the plants' situations and crew responses, the time-related factors can be evaluated in real time. The application for the dynamic HRA will be shown in the future with a development of the dynamic plant model.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] J. Bell, J. Holroyd, Review of Human Reliability Assessment Methods, RR679 Research Report, Health and Safety Executive, 2009.

[2] A.D. Swain, H.E. Guttman, Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications, NUREG/CR-1278, US Nuclear Regulatory Commission, Washington, D.C., USA, 1983, pp. 12/1–12/23.

[3] A.D. Swain, Accident Sequence Evaluation Program Human Reliability Analysis Procedure, NUREG/CR-4772, US Nuclear Regulatory Commission, Washington, D.C., 1987.

[4] M. Barriere, D. Bley, S. Cooper, J. Forester, A. Kolaczkowski, W. Luckas, G. Parry, A. Ramey-Smith, C. Thompson, D. Whitehead, J. Wreathall, Technical Basis and Implementation Guidelines for a Technique for Human Event Analysis (ATHEANA), NUREG-1624, Rev. 1, U.S. Nuclear Regulatory Commission, Washington, D.C., 2000.

[5] D. Gertman, H. Blackman, J. Marble, J. Byers, C. Smith, The SPAR-H Human Reliability Analysis Method, NUREG/CR-6883, U.S. Nuclear Regulatory Commission, Washington, D.C., 2005.

[6] J. Kim, S.J. Lee, S.C. Jang, HuRECA: the Human Reliability Analysis Method for Computer-Based Advanced Control Rooms, KAERI/TR-4385, KAERI, 2011.

[7] A. Bye, K. Laumann, C. Taylor, M. Rasmussen, S. Øie, K. van de Merwe, The Petro-HRA Guideline, IFE/HR/E-2017/001, Institute for Energy Technology, Norway, 2017, pp. 167–184.

[8] G. Parry, B. Lydell, A. Spurgin, P. Moieni, A. Beare, An Approach to the Analysis of Operator Actions in PRA, EPRI TR-100259, Electric Power Research Institute (EPRI), 1992.

[9] Y. Kim, J. Kim, J. Park, S.Y. Choi, S. Kim, W. Jung, H.E. Kim, S.K. Shin, An HRA Method for Digital Main Control Rooms — Part I: Estimating the Failure Probability of Timely Performance, KAERI/TR-7607/2019, 2019.

[10] S. French, Human Reliability Analysis: A Review and Critique, Manchester Business School Working Paper, Number 589, 2009.

[11] W. Jung, D. Kang, J. Kim, Development of a Standard Method for Human Reliability Analysis of Nuclear Power Plant, KAERI/TR-2961/2005, 2005.

[12] J.C. Williams, HEART, a proposed method for assessing and reducing human error, in: Ninth Advances in Reliability Technology Symposium 1986, NEC, University of Bradford paper B3/R, 1986.

[13] E. Hollnagel, Cognitive Reliability and Error Analysis Method (CREAM), Elsevier, 1998, pp. 245–261.

[14] D.E. Embrey, P.C. Humphreys, E.A. Rosa, B. Kirwan, K. Rea, SLIM-MAUD, An Approach to Assessing Human Error Probabilities Using Structured Expert Judgment, NUREG/CR-3518, U.S. Nuclear Regulatory Commission, Washington, D.C., 1984.

[15] A.M. Whaley, D.L. Kelly, R.L. Boring, W.J. Galyean, SPAR-H Step-by-step Guidance, INL/EXT-10-18533 Rev. 2, Idaho National Laboratory, 2011.

[16] J. Park, W. Jung, Opera — a human performance database under simulated emergencies of nuclear power plants, Reliab. Eng. Syst. Saf. 92 (2007) 503–519.

[17] Y. Kim, J. Choi, J. Park, W. Jung, S.J. Lee, Estimating diagnosis time of emergency situations in digitalized control rooms, in: Proceedings of the AHFE 2018 International Conference on Human Error, Reliability, Resilience, and Performance, 2018. July 21-25, Florida, USA.

[18] E. Lois, V.N. Dang, J. Forester, H. Broberg, S. Massaiu, M. Hildebrandt, P.Ø. Braarud, G. Parry, J. Julius, R. Boring, I. Männistö, A. Bye, International HRA Empirical Study — Phase 1 Report, NUREG/IA-0216, vol. 1, U.S. Nuclear Regulatory Commission, Washington, D.C., 2009, 2/22-2/45.

[19] J. Park, Y. Kim, J.H. Kim, W. Jung, S.C. Jang, Estimating the response times of human operators working in the main control room of nuclear power plants based on the context of a seismic event — a case study, Ann. Nucl. Energy 85 (2015) 36–46.

[20] S. Cooper, A. Lindeman, EPRI/NRC-RES Fire Human Reliability Analysis Guidelines—Qualitative Analysis for Main Control Room Abandonment Scenarios, Supplement 1, NUREG-1921, Supplement 1, EPRI 3002009215, Washington, D.C., 2020, 7/1-7/34.

[21] M. Drouin, A. Gilbertson, G. Parry, J. Lehner, G. Martinez-Guridi, J. LaChance, T. Wheeler, Guidance on the Treatment of Uncertainties Associated with PRAs in Risk-Informed Decisionmaking, NUREG-1855, Revision 1, U.S. Nuclear Regulatory Commission, 2017.

[22] J. Cho, Y. Kim, J. Kim, J. Park, D.S. Kim, Realistic estimation of human error probability through Monte Carlo thermal-hydraulic simulation, Reliab. Eng. Syst. Saf. 193 (2020) 106673.