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An Identification of PSF Lag and Linger Effects for Dynamic Human Reliability Analysis: Application of Experimental Data

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Abstract—**Many researchers have emphasized the importance of dynamic probabilistic safety assessment (PSA), which highlights the necessity of studies for dynamic human reliability analysis (HRA). Dynamic HRA concentrates on a dynamic account of human actions or how performance shaping factors (PSFs) can dynamically modify the human error probability (HEP) over time. In contrast, existing static HRA does not consider human actions as changes over time or event progressions. Accordingly, previous research on dynamic HRA conceptually suggested PSF lag and linger effects to treat dependence between operator actions in dynamic HRA versus existing approaches. As follow-up research, this study attempted to identify PSF lag and linger effects for dynamic HRA on the basis of experimental data. Firstly, mathematical models for PSF lag and linger effects were developed based on a literature survey in the field of biology. Secondly, we analyzed experimental scenarios from a control room study to identify operator actions considered in PSA. Lastly, based on the experimental data, the effect of the stress PSF with lag and linger effects was compared to that without PSF lag and linger effects. This paper concludes with an overall discussion of PSF lag and linger effects based on the relation between the stress PSF and error occurrence.**

Keywords—human reliability analysis, dynamic modeling, performance shaping factor, lag and linger effects

I. INTRODUCTION

Human reliability analysis (HRA) is an approach to evaluate human errors and provide human error probabilities (HEPs) for application in probabilistic safety assessment (PSA) [1]. To estimate HEPs, HRA generally adopts the concept of performance shaping factors (PSFs), which refer to influences on operator performance such as stress, complexity and operator experience. Most HRA methods identify relevant and risk-significant PSFs in the context of the operator task to be analyzed, then multiply their multiplier values by a nominal HEP, a default error rate that serves as the starting point of human risk quantification.

Recently, the necessity of studies for dynamic HRA (a.k.a., simulation-based or computation-based HRA) has become apparent, as many researchers have emphasized the importance of dynamic approaches to PSA [2, 3]. Existing static HRA mostly does not consider human performance changes over time or the event progression, nor do they provide a truly dynamic account of human actions or evolving PSFs that modify the HEP depending on when in the timeline the action is modeled [4]. On the other hand, dynamic HRA considers human actions dynamically and models types of activities and events even where the human role is not clearly understood or predicted, i.e., unexampled events such as severe accidents [5].

In a recent paper on dynamic HRA, Boring [6] conceptually suggested PSF *lag* and *linger* effects as an option to treat dependence between operator actions. PSF lag indicates that the effect of the PSF on performance does not immediately psychologically or physically appear, while PSF linger means that the influence of PSFs on previous operator actions is not finished after the actions, resulting in residual effects on the next operator actions.

This paper aims to identify PSF lag and linger effects for dynamic HRA on the basis of experimental data. First, mathematical models for PSF lag and linger effects are developed on the basis of a literature survey in the field of biology. Second, we analyze experimental scenarios to identify operator actions considered in PSA. For the experiment scenarios, these are based on the first author's previous experiments [7], which were performed with a full-scope simulator for the APR1400 reactor type using actual operators. Lastly, based on the experimental data, the effects of the stress PSF with and without lag and linger effects were compared to the error occurrence observed in the experiment.

II. MATHEMATICAL MODELING OF PSF LAG AND LINGER EFFECTS

Stress is a representative PSF which is postulated to have PSF lag and linger effects [6]. In the field of biology, several studies demonstrate that secretion of hormones such as cortisol [8] and corticosterone [9] affects the stress level. Based on the results of these studies, we assumed mathematical models for PSF lag and linger effects. The following sections include brief explanations on how to model PSF lag and linger effects, respectively.

A. An investigation on PSF lag effect

Lag indicates that the performance effect of the PSF does not immediately psychologically or physically respond to the event. For modeling the PSF lag effect, it is important to know the increasing trend, i.e., how they reach a maximum PSF level, and the time that it takes to reach the maximum value.

Dorin et al. [8] tried to estimate maximum cortisol secretion rates. Cortisol is a hormone that increases dramatically during adaptation to physiological stress. The results of their study include a trend that the cortisol concentrations reach maximum level, i.e., natural log function, and the time that it takes to reach the maximum value (i.e., 60min).

B. An investigation on PSF linger effect

Linger means that the influence of PSFs of previous operator actions is not finished after the actions end, and the residual PSF continues to affect the next operator actions. To identify the lingering impact of stress, Vitousek et al. [9] experimentally investigated the decrease of corticosterone hormones, which represents the decrease of stress, depending on the change over time. In the results of their study, it is identified that the concentration of the corticosterone hormone, i.e., stress, exponentially decreases depending on change of time and reaches a normal state after 180min.

C. Integrated mathematical model for PSF lag and linger effects

Fig. 1 with Eq. (1) and Fig. 2 with Eq. (2) show mathematical models of PSF lag and linger effects for a task when the time to perform a task is more than and less than 60min, respectively. The explanation on the parameters in each figure is shown in Table I.

The biggest difference between the two models concerns PSF lag time, i.e., 60min. For the first model, the time to perform a task is more than 60min, and therefore there is the time that the effect of the PSF is sustained at the end of the task. On the other hand, for the second model, the time to perform a task is less than 60min. It is finished before the PSF value reaches to maximum level due to the PSF lag.

In addition, this study only adopts PSF lag and linger effects on negative PSF multiplier values, e.g., x2 or x5, while positive PSF multiplier values are not considered.

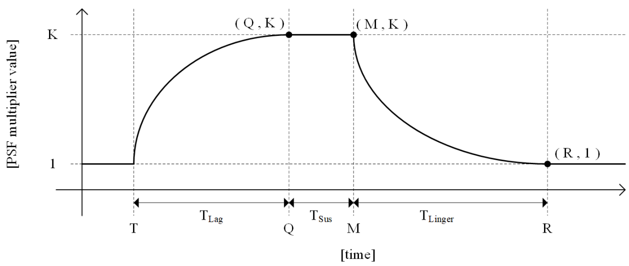

Fig. 1. A mathematical model of PSF lag and linger effects for a task when the time to perform a task is more than 60min

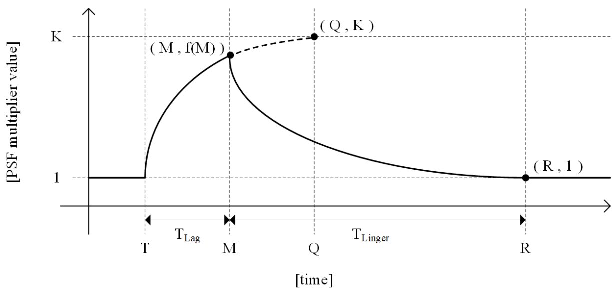

Fig. 2. A mathematical model of PSF lag and linger effects for a task when the time to perform a task is less than 60min

$$\begin{cases} y = 1 & [x < T] \\ y = \dfrac{K-1}{\ln(Q-T+1)}\ln(x-T+1)+1 & [T \le x < Q] \\ y = K & [Q \le x < M] \\ y = exp\left(-\dfrac{\ln K}{R-M}(x-R)\right) & [M \le x < R] \\ y = 1 & [R \le x] \end{cases} \tag{1}$$

$$\begin{cases} y = 1 & [x < T] \\ y = \dfrac{K-1}{\ln(Q-T+1)}\ln(x-T+1)+1 & [T \le x < M] \\ y = exp\left(-\dfrac{\ln(f(M))}{R-M}(x-R)\right) & [M \le x < R] \\ y = 1 & [R \le x] \end{cases} \tag{2}$$

TABLE I. DEFINITION OF PARAMETERS IN MATHEMATICAL MODEL

Parameter	Definition
T	Starting time of a task
Q	Time that it takes to reach a maximum PSF value in a task
M	Time to finish a task
R	Time to return to nominal PSF level (i.e., time that the PSF effect of a task is totally finished)
K	A PSF value
f(M)	A PSF value limited by lag effect when the time to perform a task is less than 60min
T_{Lag}	Delayed time to arrive at a PSF value by the lag effect (maximum 60min)
T_{Sus}	Time that the effect of PSFs is sustained by end of the task
T_{Linger}	Delayed time to return to nominal PSF level by the linger effect, i.e., 180min

III. OPERATOR ACTIONS IN EXPERIMENTAL SCENARIOS

Next, we looked at evidence from lag and linger from operator data. This paper only concentrates on two scenarios, while the first author's previous experiment includes 36 scenarios with different conditions [7]. This downselect of scenarios is because the number of available scenarios actually including operator errors is limited. The following sections provide descriptions for the experimental scenarios and operator actions involved in each scenario.

A. Experiment description

1) Scenario: Steam generator tube rupture (SGTR) + Failure of N16 indicators (i.e., masking of information – this makes the diagnosis task more difficult.), and loss of all feedwater (LOAF).

2) Measurements in the experiment: Completion time for the tasks and operator errors were measured in the experiment.

3) Participants: The experiments involved different crews according to each scenario. Each crew consisted of three actual operators, namely a shift supervisor (SS), a reactor operator (RO), and a turbine operator (TO). All the operators had operating licenses for the APR1400 reactor, which is a pressurized water reactor (PWR), or had licenses for other types of PWRs such as WH600, Framatom, OPR1000 and WH1000.

4) Facility and data acquisition: A full-scope simulator for the APR1400 reactor type was used in the experiment. Operator performance data such as time and error were collected through observation and audio/video recording.

B. Identification of operator actions modeled in PSA

Each scenario introduced in the previous section includes human failure events (HFEs), which are assumed on the basis of the APR1400 PSA model. These are also considered as important actions critical to the plant safety. The number of HFEs in each scenario depends on the length of the scenario. Tables II and III indicate the identified information for the HFEs in each scenario.

TABLE II. THE HUMAN FAILURE EVENTS MODELED IN THE SGTR + FAILURE OF N16 INDICATORS SCENARIO

	HFE 1	HFE 2
Description	Operator fails to isolate faulted Steam Generator (SG).	Operator fails to control primary pressure after SGTR.
Procedure information	Emergency operating procedure	Emergency operating procedure
Sub-tasks	Identify a faulted SG.	Diagnose the pressure control operation.
	Isolate a faulted SG.	Throttle operate safety injection.
		Operate aux. spray.
		Operate pressurizer gas vent system.

TABLE III. THE HUMAN FAILURE EVENTS MODELED IN THE LOAF SCENARIO

	HFE 1	HFE 2
Description	Operator fails to align a startup feedwater pump.	Operator fails to open pilot-operated safety relief values (POSRVs).
Procedure information	Emergency operating procedure	Recovery procedure
Sub-tasks	Open a motor-operated value.	Prepare the feed & bleed operation
	Start a startup feedwater pump.	Open POSRVs

IV. ANALYSIS OF PSF LAG & LINGER EFFECTS

A. Assumptions for identifying PSF lag & linger effects

This study analyzed the effect of the stress PSF. As mentioned in the previous section, the stress PSF is a representative PSF, which has PSF lag and linger effects [6]. In this study, we assumed the stress PSF and its multiplier value suggested by the Standardized Plant Analysis Risk-HRA (SPAR-H) [10]. Table IV indicates SPAR-H PSF levels and multiplier values for the stress PSF [10].

TABLE IV. SPAR-H PSF LEVELS AND MULTIPLIER VALUES ON STRESS PSF [10]

SPAR-H PSF	SPAR-H PSF levels	SPAR-H multipliers
Stress	Extreme	5.00
	High	2.00
	Nominal	1.00

The analysis is basically focusing on a sub-task unit. According to Boring [6], it is emphasized that dynamic HRA must account for a sub-task level rather than an HFE, because there is a dynamic dependence caused by the lingering effects of PSFs across sub-tasks [4]. Therefore, this study also analyzed the PSF level and effect of each sub-task. Tables V and VI show the stress PSF levels and multiplier values depending on sub-tasks included in each scenario. These are also assumed on the basis of the APR1400 PSA model.

TABLE V. STRESS PSF LEVELS AND MULTIPLIER VALUES DEPENDING ON SUB-TASKS IN THE SGTR+FAILURE OF N16 INDICATORS SCENARIO

Sub-tasks	PSF level	PSF multiplier
#1: Identify a faulted SG.	Extreme	5.00
#2: Isolate a faulted SG.	High	2.00
#3: Diagnose the pressure control operation	Extreme	5.00
#4: Throttle operate safety injection	High	2.00
#5: Operate aux. spray	High	2.00
#6: Operate pressurizer gas vent system.	High	2.00

TABLE VI. STRESS PSF LEVELS AND MULTIPLIER VALUES DEPENDING ON SUB-TASKS IN THE LOAF SCENARIO

Sub-tasks	PSF level	PSF multiplier
#1: Open a motor-operated value.	High	2.00
#2: Start a startup feedwater pump.	High	2.00
#3: Prepare the feed & bleed operation	Extreme	5.00

Sub-tasks	PSF level	PSF multiplier
#4: Open POSRVs	High	2.00

This study concentrates on the relation between 1) stress PSF values with and without lag and linger effects and 2) error occurrence. The other PSFs in SPAR-H equally contribute to the error occurrence. In other words, the effects of other PSFs are static, but the dynamic effect, i.e., lag and linger effect, is only applied for the stress PSF.

B. Analysis results

Fig. 3 and 4 respectively indicate a part of comparison between total stress PSF values with lag and linger effects and without lag and linger effects depending on time. These also includes the moment operator errors were observed.

The total stress PSF value with lag and linger effects is calculated by multiplying all the PSF values of sub-tasks. The maximum value is assumed as the biggest multiplier value (i.e., 5.00) of the stress PSF in SPAR-H. For the PSF value of each sub-task with lag and linger effects, it is calculated by considering mathematical models introduced in the previous section, timing data from the experiments, and stress PSF multiplier values in Table V and VI. For example, in Fig. 3, the total PSF value with lag and linger effects (i.e., 3.34) is estimated by multiplying 2.48 (i.e., the PSF value of sub-task #1) and 1.34 (i.e., the PSF value of sub-task #2) at the moment that the time is 1,430sec.

On the other hand, the total PSF value without lag and linger effects corresponds to the approach of existing static HRA. For example, the time between 1,394sec and 1,414sec in Fig. 3 is the task performance time for sub-task #1, and the PSF value is constant (i.e., 5.00) regardless of the change over time.

As a result, the total values of stress PSF with lag and linger effects are higher than those without lag and linger effects at the moment that operator errors occur (See Fig. 3 and 4). In the case of the operator error #1 and #2, these happened when the operators performed tasks which are not significantly considered in the PSA after they carried out the actions important in terms of PSA. These could be shown as indirect evidences of PSF linger effects. In addition, if we see the PSF values with lag and linger effects when the operators perform sub-task #1 in Fig. 3, it indicates two times or lower values (from 1.00 to 2.48) than those without lag and linger effects (5.00). For the moment, an operator error has not occurred. In this case, there may be the possibility that the stress PSF has a relatively low effect on the error occurrence due to the PSF lag effect, or the existing static approach using constant PSF values in HRAs is not appropriate.

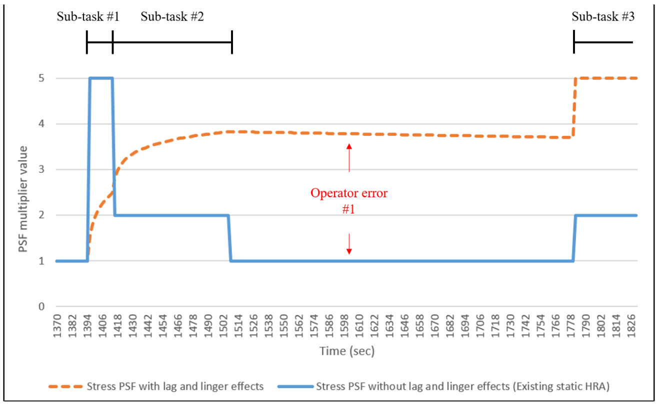

Fig. 3. A part of comparison between total stress PSF values with and without lag and linger effects in the SGTR + Failure of N16 indicators scenario

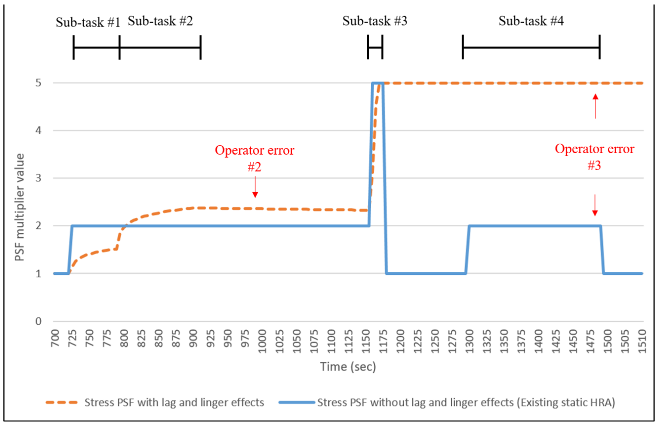

Fig. 4. A part of comparison between total stress PSF values with and without lag and linger effects in the LOAF scenario

V. CONCLUSION

This study attempted to identify PSF lag and linger effects for dynamic HRA on the basis of experimental data. Firstly, mathematical models for PSF lag and linger effects were developed on the basis of literature survey in the field of biology. Secondly, we analyzed experimental scenarios to identify operator actions considered in PSA. Lastly, based on the experimental data, the effect of stress PSF with PSF lag and linger effects was compared to that without PSF lag and linger effects. As a result, we conjectured PSF lag and linger effects based on the relation between the variation of stress PSF and error occurrence.

It is worth noting that the original formulation of PSF lag and linger [6] failed to describe the biological importance of minimizing lag. Especially for physical or bodily safety, where personal danger may be involved, it would seem maladaptive to have a PSF lag. The prevention of peril depends on quick response, not laggard reactions. Thus, some PSFs may not exhibit the lag effect at all, due to the need for expediency in executing behaviors. In other cases, lag may actually be adaptive, especially when the effect helps delay simultaneous or competing physiological or psychological responses. A lag may serve to delay one response in favor of allowing a higher priority response. More research is necessary to determine possible interactions of multiple PSFs with lag and linger. Additionally, the present study failed to look at linger effects for many long duration activities. Future research will seek more carefully controlled scenarios to enable conclusive findings. For now, it is safe to conclude that there is empirical evidence for PSF lag and linger. The exact nature of how PSF lag and linger works remains a topic for future exploration.

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