

Effects of Human-System Interface Quality Related to Automation and Passivity on Human Error Probability in Multi-Module Operations

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***Keywords : Human-System Interface, Human Error Probability, Multi-Module Operation, Automation, Passive Safety System.**

1. Introduction

The human-system interface (HSI) is the medium through which operators perceive plant state and execute control, and its quality directly conditions how reliably those tasks are performed. For this reason virtually every human reliability analysis (HRA) method treats interface quality as a performance shaping factor (PSF): THERP, SPAR-H, and ATHEANA all carry an ergonomics or HSI term that multiplies the nominal human error probability (HEP) when the interface fails to present the information a task demands [1]. An interface that misrepresents system mode, task completion status, or the relationship between an automatic agent and its plant components has been shown to raise cognitive workload, degrade situation awareness, and induce new error modes [2].

Small modular reactors (SMR) intensify this dependence. Multi-module operation assigns several reactors to one operator, staffing per module is reduced, and extensive automation and passive safety systems shift the operator's role from direct control to supervision of machine agents [2, 3]. O'Hara et al. identified the resulting human-performance issues, including lack of awareness of automation status, failure to recover a passive safety system abnormality, and human-machine interaction concerns across differing automation levels - all of which are mediated by what the interface shows [2]. Boring and Gertman likewise concluded that existing HRA methods lack the data and PSF structure to represent multi-module operation [3].

Evidence quantifying how HSI quality for automated and passive systems translates into error probability under these conditions is nevertheless scarce. Simulator validations of multi-module interface concepts have generally evaluated workload, situation awareness and task completion rather than error probability. Our own earlier work compared original and supportive HSI designs in the same multi-module environment, but likewise assessed only subjective workload and situation awareness, leaving the error consequence unquantified [4].

Prior HRA data on interface quality as a PSF are therefore drawn almost entirely from single-unit control rooms, where one operator supervises one process and the interface serves one plant. Under multi-module supervision the same interface must be read repeatedly

across concurrently evolving modules, so added information competes with attention that is already divided; whether interface support consequently reduces error probability, or displaces attention and raises it, cannot be inferred from single-unit data [2]. This gap matters because HSI quality is precisely the design variable that SMR concepts of operation propose to compensate for reduced staffing.

Accordingly, this study evaluates the effect of HSI quality for automation and passivity on human error probability under multi-module operation, using HEPs derived from a simulator experiment by the Human Reliability data EXtraction (HuREX) framework.

2. Experiment Design

2.1 Performance Shaping Factors

PSFs were selected from the taxonomies of conventional HRA methods and narrowed to those that are exclusive to, or redefined by, multi-module operation [1]. Table I lists the five factors; this study focuses on the two interface factors, the HSI quality of the passive safety system (HSI_PSS) and of the automatic system (HSI_AS), while the remaining three are retained as covariates.

Table I: PSFs and levels relevant to multi-module operation

PSF	Details	Levels
AMO	Number of accident modules the operator must act on	0.5 / 1 / 2
SS	Presence of a shift supervisor independently monitoring operator actions	Present / Absent
AH	Accident types an operator manages simultaneously	Homogenous / Heterogenous
HSI_PSS	Quality of information displayed on the HSI of the passive safety system	Original / Supportive
HSI_AS	Quality of information displayed on the HSI of the automatic system	Original / Supportive

2.2 Levels of HSI quality

Because the simulator used is not dedicated to SMRs, two of its systems were treated as analogues of the SMR

agents: the safety injection (SI) system as the automatic system, since coolant injection is initiated automatically at trip setpoints, and the auxiliary feedwater (AFW) system as the passive safety system, since it supplies the secondary side continuously once its actuation setpoint is reached [4].

Each interface was implemented at two levels. The original level is the unmodified simulator interface. The supportive level adds information derived from the principles of human-centred automation, as detailed in [4]: transparency of automation activity status, a comprehensible relationship between the automatic system and the relevant plant components, and a dedicated display element for the parameters inferred during procedure execution. Fig. 1 shows the supportive design for both systems.

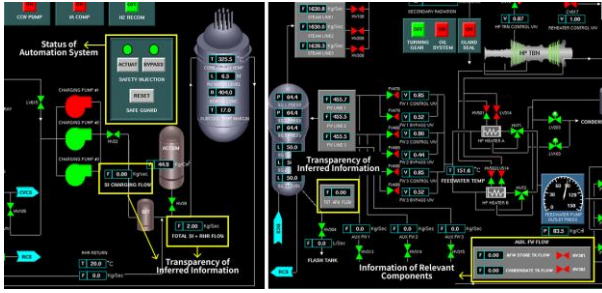


Fig. 1. Supportive HSI design for the automatic system (left) and the passive safety system (right)

2.3 Experiment setting

A four-module main control room was constructed following the Korean innovative SMR concept of operation, with each module represented by a Compact Nuclear Simulator (CNS), a three-loop Westinghouse PWR 993 MWe model developed by KAERI [4], and a large display panel showing the alarm windows of all modules. An operating crew comprised two reactor operators, each assigned up to two modules, and one shift supervisor. Fig. 2 shows the environment and the interface.

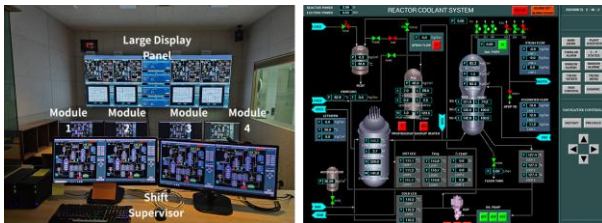


Fig. 2. Multi-module operating environment (left) and CNS user interface (right)

Scenarios combined three off-normal conditions - loss of coolant accident (LOCA), excess steam demand event (ESDE), and steam generator tube rupture (SGTR) - with, in two thirds of the cases, a simultaneous failure of the automatic system or of the passive safety system. When a system failed, the operator had to recognize the failure

and perform the recovery actions prescribed by the emergency operating procedures, so that the interface was exercised under exactly the condition it is intended to support. Table II summarizes the scenarios performed.

Table II: Experiment scenarios by operational condition

Scenario condition	Accidents	Scenarios
LOCA / ESDE / SGTR	Off-normal only	42
	+ AS failure (SI)	42
	+ PSS failure (AFW)	42

2.4 Human error probability

HEPs were derived with the HuREX framework [5]. Every procedural step performed in the experiment is decomposed into task items, each classified by cognitive activity and by a primitive task type as listed in Table III, and each item constitutes an opportunity scored from the video and audio records as a success or as an unsafe act with an error mode, either an error of omission (EOO) or an error of commission (EOC).

Table III: HuREX cognitive activities and primitive task types

Cognitive activity	Primitive task types
Information gathering (IG)	Alarm, indicator, synthesis, value, comparison, graph, abnormality, trend
Response planning (RP)	Entry, procedure, step, information, manipulation, notification
Situation interpreting (SI)	Diagnosis, identification, prediction
Execution (EX)	Discrete control, continuous control, dynamic manipulation, notification

HEP is the ratio of observed unsafe acts to demanded opportunities, as in Eq. (1), where NEOO and NEOC are the numbers of omissions and commissions and N_{event} is the total number of opportunities. Because the two error modes share this denominator, the mode-specific HEPs in Eq. (2) sum to the total HEP.

$$HEP = \frac{N_{EOO} + N_{EOC}}{N_{event}} \quad (1)$$

$$HEP_{EOO} = \frac{N_{EOO}}{N_{event}}, \quad HEP_{EOC} = \frac{N_{EOC}}{N_{event}} \quad (2)$$

The analysis covers the whole scenario, both the accident diagnosis and the subsequent response, because the recovery actions for a failed automatic or passive system are demanded in the emergency operating procedures entered after diagnosis. In total 378 accident module-runs comprising 100,236 opportunities and 283 unsafe acts were analyzed.

2.5 Statistical analysis

Because HEP is a probability estimated from a finite number of opportunities, the unsafe-act counts of each module-run were modeled directly rather than the ratio. Let y be the number of unsafe acts observed in a module-run that offered n demanded opportunities and let p be the probability that a single opportunity ends in an unsafe act, so that y follows the binomial distribution. The model relates p to the PSF levels through the logit link, as in Eq. (3).

$$\text{logit}(p) = \ln\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 HSI_{PSS} + \beta_2 HSI_{AS} + \beta_3 AMO + \beta_4 SS + \beta_5 AH \quad (3)$$

HSI_{PSS} and HSI_{AS} take the value one when the display of the passive safety system and of the automatic system, respectively, is at the supportive level, with the original level as reference; the display that is not estimable in a stratum is omitted from that model. Likewise, AMO takes 0.5 as reference for 1 and 2; SS indicates absence of the shift supervisor, with presence as reference; and AH indicates heterogeneous accidents, with homogeneous as reference. These three are retained as covariates so that the display estimates are adjusted for them. β_0 is the log-odds of an unsafe act when every factor is at its reference level. Each effect of PSF is derived via $\text{Exp}(\beta_n)$, which is the multiplier applied to the odds of error when the corresponding PSF levels change.

Models were fitted separately within each system failure mode rather than over the pooled data, because the supportive display was provided for the system that failed in a given scenario: a display is decision-relevant when its system has failed and is merely additional information when it has not, so the two situations cannot be averaged. Models were fitted over all cognitive activities and separately within each activity and error mode, with the remaining PSFs as covariates.

3. Results

3.1 HEP by system failure mode

Table IV reports the observed HEPs separately for each system failure mode, for the interface levels that vary within it. HEP was higher when a system failed than under the off-normal condition alone, as expected from the additional recovery task. The descriptive contrasts between interface levels are small relative to that level shift, and they do not adjust for the remaining PSFs, so the regression estimates below are the basis for interpretation.

Table IV: Observed HEP by system failure mode and HSI level

System failure	HSI	Level	EOO	EOC	Total
No failure	PSS	Original	3.77E-04	1.91E-03	2.29E-03
		Supportive	8.13E-04	2.39E-03	3.21E-03
	AS	Original	4.23E-04	1.86E-03	2.28E-03
		Supportive	8.38E-04	2.69E-03	3.53E-03
SI failure	AS	Original	8.25E-04	1.93E-03	2.75E-03
		Supportive	1.13E-03	1.80E-03	2.93E-03
AFW failure	PSS	Original	1.12E-03	2.31E-03	3.42E-03
		Supportive	3.29E-04	2.96E-03	3.29E-03

3.2 Binomial logistic regression

Table V gives the multipliers for the supportive level of each interface relative to its original level, within each system failure mode. Over all cognitive activities no stratum shows a significant effect, the largest being 1.475 for the automatic-system interface under no failure ($p = .082$). The effects appear once the cognitive activity is resolved, and they differ in direction between strata.

Under no failure the supportive automatic-system interface doubles the odds of a commission error in information gathering, $\text{Exp}(B) = 2.064$ ($p = .041$), while the passive-system interface runs in the opposite direction in the same activity without reaching significance, 0.545 ($p = .086$). Under safety injection failure - the condition the automatic-system display was designed for - the same display reduces the odds of a commission error in response planning to 0.323 ($p = .042$), roughly a threefold reduction. Under auxiliary feedwater failure the passive-system display shows the opposite pattern, multiplying the odds of a response-planning commission error by 4.164 ($p = .011$).

Table V: Multiplier of the supportive HSI level relative to the original level, by system failure mode (* $p < .05$)

System failure	HSI	Activity	Mode	$\text{Exp}(\beta)$	p
No failure	AS	All	Total	1.475	.082
		IG	EOC	2.064*	.041
	PSS	All	Total	0.988	.955
		IG	EOC	0.545	.086
SI failure	AS	All	Total	0.906	.711
		RP	EOC	0.323*	.042
AFW failure	PSS	All	Total	1.013	.960
		RP	EOC	4.164*	.011

4. Discussion

Interface quality does not act globally on error probability: its effect depends on whether the system the display describes has failed and on the cognitive activity

being performed, so averaging over either dimension cancels effects of opposite sign. For the automatic-system display the direction reverses with relevance. When the safety injection system failed, the display carried the actuation status and the components bearing on the recovery to be planned, and the odds of a response-planning commission error fell to about a third. When no system failed, the same elements were required by no demanded task and the odds of a commission error in information gathering doubled.

The passive-system display did not show this benefit even where it was relevant. The supportive information was added at the module level, so under multi-module supervision the operator must read it once per module while attention is already divided across concurrently evolving processes. The automatic-system display survives this cost because its content is a discrete actuation status read at a glance, whereas the passive-system display adds continuous flow parameters that must be integrated before a response can be planned - the activity in which its multiplier is largest.

The multipliers rest on modest numbers of unsafe acts and should be read as directional evidence; because the supportive display was allocated to the system that failed, only one display is estimable per failure mode; and participants were students rather than licensed operators. For design, interface support should be made conditional on relevance rather than displayed permanently, and consolidated at the crew or overview level rather than replicated per module.

Acknowledgement

This work was supported by the Innovative Small Modular Reactor Development Agency grant funded by the Korea Government (No. RS-2023-00258118).

REFERENCES

- [1] J. W. Kim and W. Jung, A Taxonomy of Performance Influencing Factors for Human Reliability Analysis of Emergency Tasks, *Journal of Loss Prevention in the Process Industries*, Vol. 16, No. 6, pp. 479-495, 2003.
- [2] J. M. O'Hara, J. C. Higgins, and M. Pena, Human-Performance Issues Related to the Design and Operation of Small Modular Reactors, NUREG/CR-7126, U.S. Nuclear Regulatory Commission, 2012.
- [3] R. L. Boring and D. I. Gertman, Human Reliability Analysis for Small Modular Reactors, INL/CON-12-25622, Idaho National Laboratory, 2012.
- [4] T. R. Kim and J. Kim, An Experimental Assessment of Human-System Interface Quality as a Performance Shaping Factor for High-Level Automation and High Passivity in Multi-Module Operation, *Proceedings of NPIC&HMIT 2025*, Chicago, Illinois, 2025.
- [5] W. Jung, J. Park, Y. Kim, S. Y. Choi, and S. Kim, HuREX – A Framework of HRA Data Collection from Simulators in Nuclear Power Plants, *Reliability Engineering & System Safety*, Vol. 194, 106235, 2020.