Application of thermal comfort theory in probabilistic safety assessment of a nuclear power plant

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Abstract Human factor errors in probabilistic safety assessment (PSA) of a nuclear power plant (NPP) can be prevented using thermal comfort analysis. In this paper, the THERP+HCR model is modified by using *PMV* (Predicted Mean Vote) and *PPD* (Predicted Percentage Dissatisfied) index system, so as to obtain the operator cognitive reliability, and to reflect and analyze human perception, thermal comfort status, and cognitive ability in a specific NPP environment. The mechanism of human factors in the PSA is analyzed by operators of skill, rule and knowledge types. The THERP+HCR model modified by thermal comfort theory can reflect the conditions in actual environment, and optimize reliability analysis of human factors. Improving human thermal comfort for different types of operators reduces adverse factors due to human errors, and provides a safe and optimum decision-making for NPPs.

Key words Thermal comfort, PSA, Nuclear safety

1 Introduction

In nuclear power industry, close attention is paid to its safety. The probability safety assessment (PSA) by analysis of human factors can provide a safe nuclear power[1–4]. The human factors are relevant to both the equipment systems and personal difference in physiology, psychology, and the behavior. In the 1970s, Fanger[5] developed the thermal comfort theory for effective analysis of human factors considering human -environment interactions.

In this paper, the thermal comfort theory is introduced into the PSA, and the influence of human factors in a nuclear power plant on PSA is obtained by using THERP+HCR model modified with the thermal comfort theory. The human comfort is improved by optimizing the ambient conditions, thus reducing adverse human factors in nuclear probabilistic safety. The results show that all safe and optimized decision-making can guarantee safety of a nuclear power plant.

2 Theoretical model

2.1 Thermal comfort theory

Comfort conditions include objective factors of temperature and humidity, and person subjective feeling under the comprehensive function influence. Fanger[5] used the index of *PMV* (Predicted Mean Vote) and *PPD* (Predicted Percentage Dissatisfied) in the thermal comfort theory to evaluate the thermal environment[5,6]. The *PMV* is the averaged human environmental thermal comfort:

$$PMV = (0.303e^{-0.036M}+0.028)\{M-W-3.05\times10^{-3}[5733-6.99(M-W)-P_f]-0.42[(M-W)-58.15]-1.7\times10^{-5}M(5867-P_f)-0.0014M(34-t_n)-3.96\times10^{-8}f_y[(t_y+273)^4-(MRT+273)^4]-f_y a_c(t_y-t_n)\} \quad (1)$$

where, M is the metabolic rate (W·m^{-2}), W is the effective mechanical power (W·m^{-2}), P_f is the partial pressure of water vapor (Pa), t_n is the air temperature (ºC), f_y and t_y is the factors of clothing surface area and its temperature (ºC), MRT is the mean radiant temperature (ºC), $C=f_y a_c(t_y-t_n)$ is the convective heat

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loss ($W·m^{-2}$), a_c is the convective heat transfer coefficient ($W·m^{-2}·°C^{-1}$). The *PMV* index defined by ISO7730 is given in Table 1. The *PPD* describes percentage of human dissatisfaction with thermal environment, and is expressed as[5,6]

$$PPD=1-0.95\exp[-(0.03353PMV^4+0.2179PMV^2)] \quad (2)$$

Table 1 *PMV* index of thermal comfort

PMV	3	2	1	0	–1	–2	–3
Thermal comfort	hot	warm	slightly warm	neutral	slightly cool	cool	cold

2.2 Cognitive reliability model

Technique for human error rate prediction (THERP) and human cognitive reliability (HCR) model[7] are widely used for human reliability analysis (HRA) in PSA of nuclear power plant. Fig.1 shows the event tree of human factors[8]. The probability of human error (P) includes the unrecoverable cognition (P_1), no-response (P_2), and the implementing key operation in terms of the emergency procedure (P_3). P_1 is generally adopted as 1.0×10^{-4} based on the symptom-oriented emergency procedure and simulative machine training theory[7].

P_3 in specific situation can be obtained in appropriate tables for human error probability in Ref.[13].

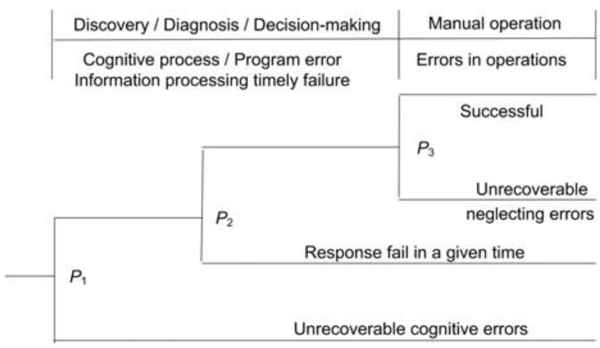

Fig.1 Event tree of human factors.

Staff behavior identification tree contains skill, rule and knowledge[7,9], and P_2 can be expressed as

$$P_2=\exp[-(t/T_{1/2}-\gamma)/(\alpha\beta)], T_{1/2}=T_{1/2,O}(1+K_1)(1+K_2)(1+K_3) \quad (3)$$

where t is allowable time (min), α is scale parameter, β is shape parameter, γ is position parameter[7], $T_{1/2}$ is modified execution time (min), and $T_{1/2,O}$ is execution time of simulative machine training (min); K_1 is operator experience, K_2 is stress level, and K_3 is man-machine interface. The values of α, β and γ are listed in Table 2, and the values of K_1, K_2 and K_3 are given in Table 3 [12].

Table 2 Values of α, β, and γ

Operator	α	β	γ
Skill	0.407	1.2	0.7
Rule	0.601	0.9	0.6
Knowledge	0.791	0.8	0.5

Table 3 Values of K_1, K_2, and K_3

Category	Correction factors		Value
Operator experience	K_1	Expert	–0.22
		Normal	0.00
		Novice	0.44
Stress level	K_2	Severe	0.44
		Potential	0.28
		None	0.00
		Relax	0.28
Man-machine interface	K_3	Excellent	–0.22
		Good	0.00
		Common	0.44
		Bad	0.78
		Poverty	0.92

2.3 Cognitive reliability model in specific scene

THERP+HCR model was used in China's Daya Bay Nuclear Power Plant and Ling Ao Nuclear Power Plant. It did promote the NPPs' construction and operation, but it has been found that many data of the model cannot fully reflect the actual ambient conditions and human performance in the experiment. According to the comfort theory, human subjective feelings are affected by comprehensive factors. The THERP+HCR model modified by comfort theory can reflect the actual ambient conditions and optimize the reliability of human factor analysis.

Using the thermal comfort theory, Eq. (3) for calculating P_2 is with the modified execution time:

$$T_{1/2}=T_{1/2,O}(1+K_1)[1+(1.05-PPD)K_2](1+K_3),K_2\leq 0 \quad (4)$$

$$T_{1/2}=T_{1/2,O}(1+K_1)[1+(0.95+PPD)K_2](1+K_3), K_2\geq 0 \quad (5)$$

Stimulated by all kinds of external environment factors, the body stress means the non-specific reactions, including molecular biological chemistry, hormone level control, cognitive and emotion changing in the system integration, and so on. Because the brain hormone turning up on the stress state plays an important role in memory regulation, moderate stress is conducive for the body[10]. The modified K_2 values are listed in Table 4.

Table 4 Values of the modified K_2.

Severe stress	Medium stress	Without stress	Potential stress	Relax stress
0.44	0.28	0	–0.1	–0.15

3 Simulation and analysis of *P* values

The heat transfer tube in a steam generator (SG) rupture accident[7] is used to simulate and analyze the *P* values.

(1) The operator finds alarm of high radiation in secondary side works in 20 s, and calls the safety engineer. According to Section 2.2, P_1=1.0×10^{-4};

(2) The safety engineer comes in 5 min and executes SPI (continuous surveillance after incident and accident) procedure to watch on related parameters. The operator of second loop identifies and isolates the malfunctioning SG in terms of the SPI procedure. When the high-pressure injection loses within 1 min, the safety engineer orders the operator to start manual safe injection at ΔT_{sat} of less than 10ºC, indicating that the safe injection is unavailable. The safety engineer decides to execute SPU (ultimate surveillance during use of U procedure) procedure (the SPI executing time is 10 min), and takes 4 min to identify the usability of safety injection system and SG. If necessary, the operator can perform additional operations within 1 min. P_2 is calculated by HCR model using data of the event. The reactor core can be melted in 60 min, t=60–5.0–1×2×1.44=52.12 min, and $T_{1/2,O}$=10.0+4.0=14.0 min.

In the most favorable condition, K_1=–0.22 (expert), K_2 = 0 (none), and K_3 = –0.22 (excellent). Then, $T_{1/2}$= 14.0 × (1–0.22) (1–0.22) =8 .518 min, and $P_{2\ \mathrm{skill}}$=1.15×10^{-7}, $P_{2\ \mathrm{rule}}$ = 2.58×10^{-4}, and $P_{2\ \mathrm{knowledge}}$ = 4.61×10^{-3}.

In the most unfavorable condition, K_1 = 0.44 (novice), K_2 = 0.44 (severe stress) and K_3= 0.92 (poverty). Thus, $T_{1/2}$=14.0×(1+0.44)(1+0.44) (1+0.92) = 55.738 min, and $P_{2\ \mathrm{skill}}$=0.5, $P_{2\ \mathrm{rule}}$=0.512 and for $P_{2\ \mathrm{knowledge}}$ =0.918.

In a general condition, K_1=0 (normal knowledge), K_2 =0.28 (potential stress), and K_3 =0 (good). In HCR model, $T_{1/2}$=17.92 min, $P_{2,\mathrm{skill}}$ = 1.49×10^{-3}, $P_{2,\mathrm{rule}}$ =3.49×10^{-2}, and $P_{2,\mathrm{knowledge}}$ =0.119. Using modified HCR model, $T_{1/2}$ in Eqs.(4) and (5) is modified by *PPD*, the relation of *PPD* with *PMV* is expressed by Eq.(2), and P_2 is calculated by Eq.(3). Table 5 shows the execution times based on modified HCR model.

Table 5 Execution time based on modified HCR model.

PMV	$T_{1/2}$ / min	$P_{2,\mathrm{skill}}$	$P_{2,\mathrm{rule}}$	$P_{2,\mathrm{knowledge}}$
From –0.5 to +0.5, comfortable	12.6	3.98×10^{-5}	5.01×10^{-3}	1.21×10^{-1}
	12.67	4.26×10^{-5}	5.19×10^{-3}	1.23×10^{-1}
±1, slightly warm/cool	12.89	5.23×10^{-5}	5.76×10^{-3}	1.29×10^{-1}
±2, warm/cool	13.61	9.83×10^{-5}	7.94×10^{-3}	1.47×10^{-1}
±3, hot/cold	13.92	1.27×10^{-4}	9.02×10^{-3}	1.56×10^{-1}

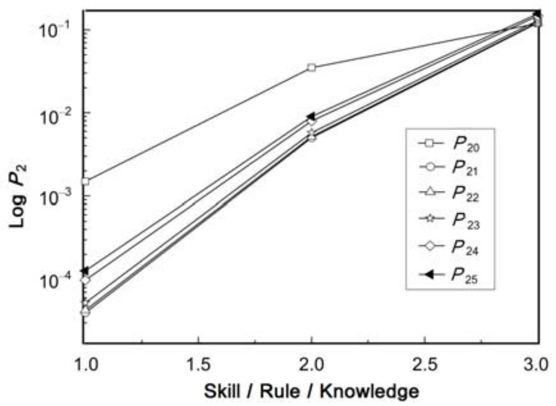

Fig.2 Error probability comparison of skill (1), rule (2) and knowledge (3).

Figure 2 shows the relationship of logP_2 with skill, rule and knowledge on the thermal comfort conditions. P_{20} corresponds to the HCR model, and P_{21}–P_{25} correspond to the modified HCR model on comfortable case 1 (*PMV*, –0.5), case 2 (*PMV*, 0.5), slightly warm/cool (*PMV*, ±1), warm/cool (*PMV*, ±2), and hot/cold condition (*PMV*, ±3), respectively. The results show that every P_2 increases with the skill, rule, and knowledge under different *PMV* index. By considering the revised K_2, the error probabilities of skill and rule are less than those of the original HCR model. Error probability of knowledge for inexperience is the biggest. Under the extreme changes from comfort to hot or cold, the influence of P_2 increases less than that of operator type.

(3) At unavailable safety injection, the safety engineer orders the operator of the second loop to open fully the exhausting and condenser valves so as to cool reactor core quickly, and the operator performs these operations within 1 min. If the implement of rapid cooling within 60 min is not successful, the reactor core will be melted. Fig.3 shows the event tree of human factors for valve operations.

P_3 represents the probability of F_1 and F_2. The error probability of safe injection of 6×10^{-4} in the tables of estimated human error probabilities in Ref.[13] is corrected as 1.2×10^{-3} when considering the number of group on the shift is 2. Similarly, the error probability of operating valve of 3×10^{-3} [13] is corrected as 6×10^{-3}. Due to the low correlation between the shift supervisor and operator, the monitoring error probability is $P_n=(1+19N)/20$[13], where, N is the probability of failure. So, $P_{A2}= 5.57\times10^{-2}$, $P_{B2}= 5.29\times10^{-2}$, $P_{A1}=1.2\times10^{-3}$, and $P_{B1}=6\times10^{-3}$. The $F1$ and $F2$ are the error paths in Fig.3, and their error probability are $P_{F1}=P_{A1}\times P_{A2}= 6.68\times10^{-5}$, and $P_{F2}=P_{B1}\times P_{B2}=3.17\times10^{-4}$. Total operating errors ($P_3=P_{F1}+P_{F2}$) is 3.84×10^{-4}. Table 6 shows the human error probability (P) based on HCR model and modified HCR model respectively. P_2 plays a leading role in the total human error probability. In the case of *PMV*= slightly warm/cool, the leading human error probability is P_3 for a skill type operator, P_3 and P_2 for a rule type operator, and P_2 for a knowledge type operator. Of all the three personnel types in Table 2, the human error probability of the knowledge type is the biggest.

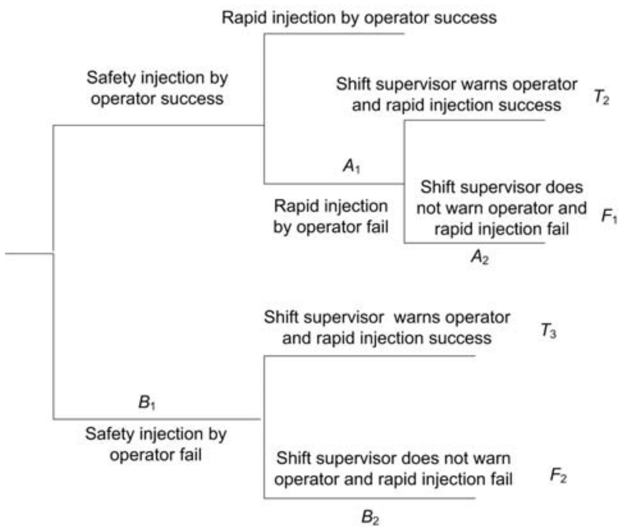

Fig.3 Human factors event tree of valve operations.

Table 6 Human error probabilities based on HCR and modified HCR model.

PMV	$P_1+P_{2,skill}+P_3$	$P_1+P_{2,rule}+P_3$	$P_1+P_{2,knowledge}+P_3$
None	1.97×10^{-3}	3.54×10^{-2}	1.19×10^{-1}
±1slightly warm/cool	7.62×10^{-4}	1.20×10^{-2}	1.29×10^{-1}

4 Conclusion

The impact of environment changing on the error probability is considered based on the modified HCR model. The error probability increases in the uncomfortable environment conditions. Operators of skill, rule, and knowledge types let unrecoverable cognitive, no-response and operation error play the leading role in the total human error probability. So, taking proper measures corresponding to the operator types can be used to improve security. The ambient conditions of an NPP can be optimized by the modified THERP+HCR model, thus improving human body comfort, and reducing disadvantageous factors of nuclear safety.

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