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RESEARCH ON NONDESTRUCTIVE TESTING AND EVALUATION METHOD OF HEAT TRANSFER TUBE BASED ON PROBABILITY THEORY

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ABSTRACT

COVID-19 The integrity evaluation of heat transfer tubes is an important part of nuclear power safety. The capability evaluation of nondestructive testing is an inevitable requirement for the development of quality evaluation. On the basis of case analysis, two parameters of uncertainty (M) and detection credibility (N) are introduced to evaluate nondestructive testing capability. The uncertainty is expressed by the relative value of the difference between the detection failure probability and the real failure probability. Based on the theory of total probability, the mathematical relationship between the detection uncertainty and the parameters of missed detection rate and false detection rate is established. The detection credibility (N) is expressed by the average value of the sum of the detection rate P(A1/B1) of failure tube and the detection rate P(B1/A1) of the conditional failure tube. Based on Bayes formula, the mathematical model of the detection reliability, the missed detection rateand the false detection rate is established. The research results can provide a reference for the in-depth study of NDT capability evaluation technology.

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INTRODUCTION

Nuclear energy as a clean energy to solve the problem of energy allocation in China, but the economy, reliability and safety of nuclear power generation is a hot topic. The Steam generator (SG) is the connection hub of primary and secondary circuits of PWR nuclear power plant, which is the weakest link of the second radiation protection. As the pressure boundary of primary circuit, the integrity of heat transfer tube guides the safe operation of nuclear power plant [Myeong-Woo Lee, 2017; Xiaoxin Zhao , 2019]. The rupture of the heat transfer tube caused serious consequences such as leakage of radioactive materials and shutdown of nuclear power plants, which played an important role in the accident of nuclear power plant [Do Haeng Hur et al., 2015; Lu Huaxing, 2011]. Nondestructive testing technology provides a basis for judging the integrity of steam generator heat transfer tubes, but there is a lack of research on the evaluation of nondestructive testing capability. In this paper, the probability theory is used as the guiding ideology to evaluate the non-destructive testing capability of the failure of heat transfer tubes, hoping to provide a reference for the efficient operation and safe production of nuclear power system.

Case analysis: In the experience of nuclear power operation ,there are many factors of heat transfer tube degradation. The ability of nondestructive testing for heat transfer tube is the evaluation basis for the comprehensive damage and degradation of heat transfer tube. The methods of evaluating NDT capability can be considered from the following aspects. Suppose B1 represents the failure event of heat transfer tube, that is, the event that the degradation has reached the safety critical value; B2 represents the normal event of heat transfer tube, i.e. the event in a safe state; A1 indicates that the failure event of the heat transfer tube is detected, i.e. it is determined that the safety critical value has been reached; A2 indicates that the normal event of the heat transfer tube is detected, i.e. the inspected tube is deemed to be in a safe state; P (A1) indicates the probability of detecting the failed pipe; P (A2) indicates the probability of detecting the normal pipe;

$$P(A_1)+ P(A_2)=1 \quad (1)$$

P (B1) represents the probability of real failure pipe; P (B2) represents the probability of real normal pipe;

$$P(B_1)+ P(B_2)=1 \tag{2}$$

B1 and B2 constitute a complete sample space, and A1 and A2 constitute a complete sample space.

According to the basic theory of probability theory, the expression of conditional probability has the following significance； setting:

$P(A_1/B1)=\gamma_1$, Indicates the detection rate of the failed heat transfer tube
$P(B_1/A_1)=\gamma_2$, Indicates the detection rate of conditional failure tubes.
$P(A_2/B_2)=\gamma_3$,, Indicates the detection rate of normal heat transfer tube;
$P(B_2/A_2)=\gamma_4$, Indicates the detection rate of normal heat transfer tube;
$P(A_2/B_1)=\beta_1$, $\beta_1$is called false detection rate.
$P(A_1/B_2)=\alpha_1$, α_1 is called the omission rate.

$$P(A_1/B_1)+ P(A_2/B_1)=\gamma_1+\beta_1=1 \tag{3}$$

$$P(A_1/B_2)+ P(A_2/B_2)=\alpha_1+\gamma_3=1 \tag{4}$$

Set 100 heat transfer tubes as the samples to be tested, 94 of which are normal samples and 6 of which are failure samples.

Detection I: Set x failed heat transfer tubes are detected (x < 6, and all of them are x real failed heat transfer tubes).The detection threshold of the detection instrument is set higher, fewer failed heat transfer tubes are detected, and 6-x are not detected .

Detection II: Set x failed heat transfertubes be detected (x=6, and include 6 real failed tubes).The determination threshold of the detection instrument is set to be moderate, and all the real failed tubes are detected.

Detection III: Set x failed heat transfer tubes be detected (x>6, and include 6 real failed tubes).The detection instrument is set with a low judgment threshold, and the number of failed tubes detected is greater than the actual number of failed tubes.

Detection IV: Set 6 failed heat transfer tubes (including 5 real failed tubes + 1 normal tube).The determination threshold setting is moderate, but the accuracy of the detection instrument is low, 1 false detection and 1 missed detection.

Detection V: Suppose 6 failed heat transfer tubes (including: 4 failed tubes + 2 normal tubes) are detected.The determination threshold is set moderately, but the accuracy of the detection instrument is low, 2 false detections and 2 missed detections.

Detection □: It is assumed that 6 failed heat transfer tubes are detected (including: 3 failed tubes + 3 normal tubes).The determination threshold is set moderately, but the accuracy of the detection instrument is very low, 3 false detections and 3 missed detections.

Detection □: Set 6 failed heat transfer tubes (including 2 failed tubes + 4 normal tubes).The determination threshold setting is moderate, but the accuracy of the detection instrument is too low, 4 false detection and 4 missed detection.
Detection □: Set 6 failed heat transfer tubes (including: (6-y) failed tubes + y normal tubes)

Table 1 shows the probability of eventsrelated to detection I, II and III . From table 1, it can be seen that the uncertainty degree M of detection can be expressed by the value of [P (A1) - P (B1)] / P (B1) = M. According to table 1, M = [P (A1) - P (B1)] / P (B1) = (X-6) / 6. When the probability of detecting the failure pipe is equal to that of the real failure pipe, M = 0, indicating that the uncertainty of detection is zero; when the probability of detecting the failure pipe is greater than that of the real failure pipe, M > 0, indicating that there is a certain uncertainty; when the probability of detecting the failure pipe is less than that of the real failure pipe, M< 0, indicating that there is a certain degree of uncertainty. If the probability of detecting the failure pipe is equal to that of the real failure pipe, but due to the problem of detection sensitivity, the detected failure pipe and the real failure pipe are not exactly the same. Although the uncertainty of detection M is still zero, there is still a big problem of unreliability. It can be seen that it is not enough to use only one evaluation parameter (uncertainty M) to evaluate NDT capability. As follows, another evaluation parameter (detection reliability N) will be introduced. Table 2 probability of detection □, □, □, □ and □ related events. It can be seen from table 2 that the probability of detecting the failure pipe is the same as that of the real failure pipe. If the detected failure pipe is not the same as the real failure pipe, it can still be expressed by the conditional probability parameter.It can be seen from table 2 that both P (A1/B1) and P (B1/A1) are related to the number of missed and false detection pipes. The detection reliability (N) can be expressed by [P (A1/B1) + P (B1/A1)]/ 2 = $[\gamma_1+\gamma_2]/2$ = N. It can be seen from table 1 that a single P (A1/B1) can only represent the situation of test I, and a single P (B1 / A1) can only represent the situation of test III, [P (A1/B1) + P (B1/A1)]/2=N can include all situations. $[\gamma_1+\gamma_2]/2=N$, $\gamma_1, \gamma_2>0$

Table 1 Probability of I, II and III Related Detecting Events

	Detection□	Detection□	Detection□	Remarks
$P(A_1)$	x%	6%	x%	$[P(A_1)-P(B_1)]/P(B_1)=M$
$P(A_2)$	(100-x)%	94%	(100-x)%	
$P(B_1)$	6%	6%	6%	
$P(B_2)$	94%	94%	94%	
$P(A_1/B_1)=\gamma_1$	x/6	100%	100%	$(\gamma_1+\gamma_2)/2=N$
$P(B_1/A_1)=\gamma_2$	100%	100%	6/x	
$P(A_2/B_2)=\gamma_3$	100%	100%	(100-x)/94	Notsensitiveto credibility
$P(B_2/A_2)=\gamma_4$	94/(100-x)	100%	100%	Not sensitive to credibility
$P(A_2/B_1)=\beta_1$	(6-x)/6	0%	0%	
$P(B_1/A_2)=\beta_2$	(6-x)/(100-x)	0%	0%	
$P(A_1/B_2)=\alpha_1$	0%	0%	(x-6)/94	
$P(B_2/A_1)=\alpha_2$	0%	0%	(x-6)/x	
Detection uncertainty *M**	(x-6)/6	0	(x-6)/6	
Detection uncertainty *N***	(6+x) /12	100/100	(18-x)/(2x)	

Table 2. Probability of □,□,□,□ and □ Related Detecting Events

	DetectionⅣ	DetectionⅤ	DetectionⅥ	Detection□	DetectionⅧ
$P(A_1)$	6%	6%	6%	6%	6%
$P(A_2)$	94%	94%	94%	94%	94%
$P(B_1)$	6%	6%	6%	6%	6%
$P(B_2)$	94%	94%	94%	94%	94%
$P(A_1/B_1)=\gamma_1$	5/6	4/6	3/6	2/6	(6-y)/6
$P(B_1/A_1)=\gamma_2$	5/6	4/6	3/6	2/6	(6-y)/6
$P(A_2/B_2)=\gamma_3$	93/94	92/94	91/94	90/94	(94-y)/94
$P(B_2/A_2)=\gamma_4$	93/94	92/94	91/94	90/94	(94-y)/94
$P(A_2/B_1)=\beta_1$	1/6	2/6	3/6	4/6	y/6
$P(B_1/A_2)=\beta_2$	1/94	2/94	3/94	4/94	y/94
$P(A_1/B_2)=\alpha_1$	1/94	2/94	3/94	4/94	y/94
$P(B_2/A_1)=\alpha_2$	1/6	2/6	3/6	4/6	y/6
Detection uncertainty *M**	0	0	0	0	0
Detection uncertainty *N***	5/6	4/6	(3/6	2/6	[(6-y)/6]

Based on the total probability theory, a two parameter nondestructive testing capability evaluation model is established with the missed detection rate (α) and error detectionrate (β) as variables

Evaluation method of NDT capability for steam generator tube failure based on probability theory: Evaluation method of NDT capability of steam generator tube failure based on the concept of full probability According to the concept of total probability, a complete sample space is formed in B1 and B2, and the probability of failure pipe detected in practice is:

$$P(A_1)=P(B_1)P(A_1/B_1)+P(B_2)P(A_1/B_2) \quad (5)$$

$$\frac{P(A_1)-P(B_1)}{P(B_1)}=-P(A_2/B_1)+\frac{P(B_2)}{P(B_1)}P(A_1/B_2) \quad (6)$$

The absolute value of the relative value of the difference between the probability of detection of failure and the probability of real failure pipe, which can be used to represent the reliability of nondestructive testing. It can be seen from table 1 that M can be used as the evaluation parameter of NDT capability, which is defined as "uncertainty parameter (M) of NDT". There are:

$$M=\left|\frac{P(B_2)}{P(B_1)}P(A_1/B_2)-P(A_2/B_1)\right| \quad (7)$$

$P(A_2/B_1)=\beta_1$ is the rate of false detection which indicates the probability of normal detection under the condition of failed heat transfer tube.

$P(A_1/B_2)=\alpha_1$ is the rate of missed detection, which indicates the probability of failure in normal samples.

$\frac{P(B_2)}{P(B_1)}=\eta$ represents the ratio of the probability of the real normal tube to the real failure tube,which is the parameter of the quality of the heat transfer tube, and independent of the detection process. It is called the quality coefficient.Can be obtained from formula (7)

$$M = |\eta\alpha_1 - \beta_1| \quad (8)$$

Formula (8) shows that the uncertainty M is related to the missed detection rate α_1 and the false detection rate β_1. The uncertainty M reflects the accuracy of the determination threshold setting of the detection instrument. The threshold setting is too high, the false detection rate is low, but the missed detection rate is high. The threshold setting is too low, the false detection rate is high, but the missed detection rate is low. When M = 0, $\eta\alpha_1 = \beta_1$ the false detection rate and the missed detection rate meet a specific proportion, and the setting of the judgment threshold is the most accurate; when M > 0, $\eta\alpha_1 > \beta_1$ the missed detection rate is on the high side, and the setting of the judgment threshold is on the high side; when M<0, $\eta\alpha_1 < \beta_1$ the missed detection rate is on the low side, and the setting of the judgment threshold is on the low side. M is a parameter to determine the NDT capability by determining whether the detection threshold setting is accurate

Evaluation method of non-destructive flaw detection capability of nuclear power heat transfer tubes based on Bayes formula: According to Bayes formula

$$P(B_1/A_1) = \frac{P(B_1)P(A_1/B_1)}{P(B_1)P(A_1/B_1) + P(B_2)P(A_1/B_2)} \quad (10)$$

$$P(B_1/A_1) = \frac{1}{1 + \frac{P(B_2)}{P(B_1)} \cdot \frac{P(A_1/B_2)}{1 - P(A_2/B_1)}} \quad (11)$$

$$P(B_1/A_1) = \frac{1}{1 + \eta \cdot \frac{\alpha_1}{1-\beta_1}} = \frac{1-\beta_1}{1-\beta_1+\eta\alpha_1}$$

$$P(B_1/A_1) = \frac{1-\beta_1}{1-\beta_1+\eta\alpha_1} \quad (12)$$

According to formula (10):

$$P(A_1/B_1) = P(B_1/A_1) \cdot [P(A_1/B_1) + \frac{P(B_2)}{P(B_1)} P(A_1/B_2)] \quad (13)$$

$$P(A_1/B_1) = \frac{1-\beta_1}{1-\beta_1+\eta\alpha_1} \cdot [1-\beta_1+\eta\alpha_1] = 1-\beta_1$$

$$P(B_1/A_1) + P(A_1/B_1) = \frac{1-\beta_1}{1-\beta_1+\eta\alpha_1} + 1 - \beta_1 = \frac{(1-\beta_1)(2-\beta_1+\eta\alpha_1)}{1-\beta_1+\eta\alpha_1}$$

$$[P(B_1/A_1) + P(A_1/B_1)]/2 = N$$

Suppose that N represents the average value of the sum of the detection rate P(A1/B1) of the failed pipe and the detection rate P(B1/A1) of the conditional failed pipe, which can be used to represent the reliability of NDT. It can be seen from Table 2 that N can be used as the evaluation parameter of NDT capability, which is defined as "reliability parameter (N) of NDT evaluation". Available:

$$\mathrm{N} = [\frac{(1-\beta_1)(2-\beta_1+\eta\alpha_1)}{1-\beta_1+\eta\alpha_1}]/2 \quad (14)$$

Conclusion

Based on the case analysis, this paper introduces a two-parameter evaluation method of nondestructive testing (NDT) with detection uncertainty (M) and detection reliability (N).The detection uncertainty represents the absolute value of the ratio of the difference between the probability of detecting the failed heat transfer tube and the probability of real failure heat transfer tube to the probability of real failure heat transfer tube .Based on the full probability theory, the mathematical relationship between the detection uncertainty (M) and the parameters of the omission rate and the error rate is established.The research shows that the uncertainty M is related to the rate of false detection and the rate of missed detection.Uncertainty can be measured by measuring the rate of error and omission.The uncertainty M reflects the accuracy of the determination threshold setting of the testing instrument. The uncertainty can be reduced by adjusting the threshold setting and reducing the false detection rate and missed detection rate. The detection reliability (N) is expressed as the average of the sum of the detection rate of the failed heat transfer tube P(A1/B1) and the detection rate of the conditional failed heat transfer tube P(B1/A1). According to the Bayes formula, the mathematical model of the detection credibility N and the parameters of missed detection rate and false detection rate is established. The credibility of the test reflects the quality of the test equipment, the sensitivity of the test equipment and the test quality level of the test personnel. The reliability of detection can be improved by reducing the false detection rate and missed detection rate. Through the dual-parameter evaluation, the evaluation level of the non-destructive testing ability is further improved.

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