NTHAS8: The Eighth Japan-Korea Symposium on Nuclear Thermal Hydraulics and Safety
Beppu, Japan, December 9-12, 2012
Paper Number N8P1094

STUDY ON RELIABILITY OF DOUBLE-WALL-TUBE TYPE STEAM GENERATOR FOR SODIUM COOLED FAST REACTOR BASED ON PROBABILISTIC FRACTURE MECHANICS

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ABSTRACT

In a steam generator of sodium cooled fast reactor, sodium-water reaction would take place when the heat transfer tube fails. In order to prevent the sodium-water reaction, a double-wall-tube is considered in the 4S reactor. Accordingly, it is important to investigate an advantage of the double-wall-tube system quantitatively comparing with a single-wall-tube system. In this study, we evaluated the failure probabilities of single-wall-tube, inner and outer tube of double-wall-tube using PRAISE code in which the probabilistic fracture mechanics (PFM) method is taken into account. Failure causes are considered stress corrosion crack (SCC) and fatigue by thermal transient due to start-stop operation at weld zone. We classified process that sodium-water reaction occurs at double-wall-tube into three. Based on failure probabilities, we calculated probabilities of sodium-water reaction of single-wall-tube and double-wall-tube. In this case, it is concluded that probability of sodium-water reaction of double-wall-tube is smaller than that of single-wall-tube.

1. INTRODUCTION

In a steam generator of sodium cooled fast reactor, water and sodium exist and are separated via heat transfer tubes. When the heat transfer tube fails, sodium-water reaction would take place. So it is important to enhance safety of steam generator. In order to prevent the sodium-water reaction, double-wall-tube system is considered in the 4S reactor. 4S (Super-Safe, Small and Simple) is suitable for supplying energy to remote communities and requires no fuel replacement for thirty years. (Ueda *et al.*, 2003) It is considered double-wall-tube system reduces possibility of sodium-water reaction comparing with single-wall-tube system. Inert gas goes into sodium when outer tube is broken and water goes into inert gas when inner tube is broken because gap layer of double-wall-tube is filled with inert gas. Therefore when one side tube is broken, crack can be detected before the sodium-water reaction occurs. Many studies about double-wall-tube have been carried out qualitatively. It is important to investigate an advantage of the double-wall-tube system quantitatively comparing with a single-wall-tube system.

In this study, failure probabilities of each tube is calculated using PRAISE code in which the probabilistic fracture mechanics (PFM) method is taken into account. Stress corrosion crack (SCC) and fatigue by thermal transient due to start-stop operation at weld zone are selected as a failure causes. Probabilities of sodium-water reaction are evaluated from failure probabilities. About double-wall-tube, the scenario of sodium-water reaction is classified into independent failure, dependent failure and common cause failure. Then reaction probabilities of each scenario are evaluated and sum of these probabilities are considered to be the reaction probability on double-wall-tube system.

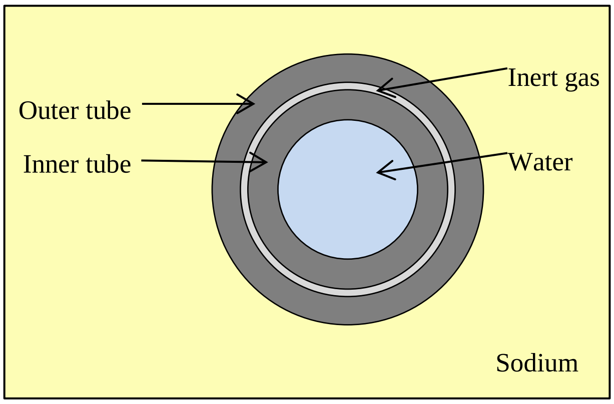

Fig. 1 Double-wall-tube system

2. INVESTIGATION OF FAILURE PROBABILITY OF EACH TUBE

2.1 Outline of PRAISE code

PRAISE (Piping Reliability Analysis Including Seismic Events) is a probabilistic fracture mechanics computer code to evaluate the reliability of welds in nuclear power plant piping systems. (Harris *et al.*, 1992) Figure 2 is a flow chart of the PRAISE model. All cracks are considered to start as semi-elliptical interior surface cracks by PRAISE as shown in Fig.3. Some of inputs, such as initial crack size, are considered to be random variables. Their values fall within a given range by the defined probability. PRAISE evaluates the failure probability as a function of time by performing a series of deterministic lifetime calculations. In this way a histogram of lifetimes is generated, from which the failure probability is derived. This process is named Monte Carlo simulation. In PRAISE, failure probabilities of SCC and fatigue crack can be calculated. This code is adjusted to welds in heat transfer tubes by changing the input data.

<SCC>

Three conditions are required for stress corrosion cracks initiation in austenitic materials. These are related to sensitization, stress and environment. The time to initiation is considered to be a random variable depending on D parameter. This parameter is assumed as following equation.

$$D = f_1(material)\, f_2(environment)\, f_3(loading) \quad (1)$$

f_1: Function of sensitization of material [-]
f_2: Function of environment [-]
f_3: Function of strain rate [-]

The PRAISE code has built in features of SCC growth in stainless steel of 304 and 316.
SCC growth rate da/dt is shown in the following equation.

$$\log(da/dt) = C_1 + C_2\left[C_3 \log(f_2) + C_4 K\right] \quad (2)$$

a : Crack length [inch]
t : Time [year]
K: Stress intensity factor [-]
$C_{1\sim4}$: Constant related to material [-]

<Fatigue crack>

It is assumed that initial crack exists and that crack size and frequency depend on distribution. The PRAISE code has built in features of fatigue crack growth in the two most commonly used materials, ferritic and austenitic steels.
Fatigue crack growth rates, da/dN and db/dN, are expressed as following equations.

$$\frac{da}{dN} = \begin{cases} 0 & , \dfrac{\Delta K_a}{\sqrt{1-R}} \le K_0 \\ C\left(\dfrac{\Delta K_a}{\sqrt{1-R}}\right)^m & , \dfrac{\Delta K_a}{\sqrt{1-R}} > K_0 \end{cases} \quad (3)$$

$$\frac{db}{dN} = \begin{cases} 0 & , \dfrac{\Delta K_b}{\sqrt{1-R}} \le K_0 \\ C\left(\dfrac{\Delta K_b}{\sqrt{1-R}}\right)^m & , \dfrac{\Delta K_b}{\sqrt{1-R}} > K_0 \end{cases} \quad (4)$$

a: Crack length for depth direction [inch]
b: Crack length for surface length direction [inch]
N:Number of cycles[-]
C:Constant in the crack growth law [-]
m:Exponent for fatigue crack growth equation [-]
$K_{o:}$ Threshold for fatigue crack growth [ksi $in^{1/2}$]
ΔK_a, ΔK_b=K_{max}-K_{min} [ksi $in^{1/2}$]
R=K_{min}/K_{max}[-]

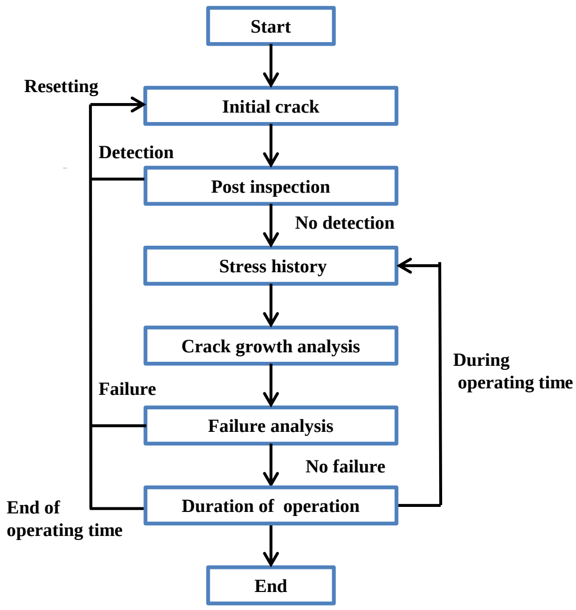

Fig. 2 Flow chart of PRAISE

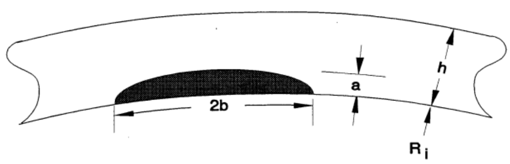

Fig. 3 Geometry of part-circumferential interior surface crack considered

2.2 Analytical condition

This subsection explains analytical condition of steam generator for SCC and fatigue crack. Table 1 shows each values of analytical condition. In addition, it is assumed that maximum operating time is thirty years and tubes have no deadweight stress because of support plates.

Table 1 Analytical condition

	Single tube	Inner tube	Outer tube
Wall thickness (mm)	3.8	3.0	2.9
Inside diameter (mm)	24.2	19.0	25.7
Internal pressure (MPa)	15.0	15.0	1.0
External pressure (MPa)	0.5	1.0	0.5

2.2.1 SCC

Material of heat transfer tube used in 4S reactor is Mod.9Cr-1Mo steel. In this study, 304 stainless steel is used instead of Mod.9Cr-1Mo steel as material constant. It is considered that SCC on outer tube occurs only when inner tube is broken because outer tube is not contacted with water while normal operating condition. Internal pressure of outer tube is assumed as that of inner tube.

2.2.2 Fatigue by thermal transient

Fatigue crack by thermal transient due to start-stop operation is considered. It is assumed that arrival time for transient is one year. Temperature difference between outer surface and inner surface of double-wall-tube is bigger than that of single-wall-tube because heat transfer coefficient of double-wall-tube is lower than that of single-wall-tube in a radial direction. Therefore, thermal stresses are different between double-wall-tube and single-wall-tube for transient. Axial thermal stress, σ_z, and temperature distribution, T_r, are described in the following equations. (JSME, 2005)

$$\sigma_z = \frac{\alpha E}{1-\upsilon}\left(\frac{1}{b^2-a^2}\int_a^b Trdr - T_2\right) \quad (5)$$

$$T_r = \frac{T_2 \ln(r/a) + T_1 \ln(b/r)}{\ln(b/a)} \quad (6)$$

T_r: Temperature distribution in a radial direction [K]
α: Linear expansion coefficient [1/K]
E: Young's modulus [MPa]
ν: Poisson ratio [-]
T_1: Outside surface temperature [K]
T_2: Inside surface temperature [K]

α, E and ν values are given by Table2 if material is Mod.9Cr-1Mo steel. Calculation results are shown in Table 3.

Table 2 Material values

Property	α[1/K]	E[MPa]	ν[-]
value	12.3E-6	1.80E+5	0.27

Table 3 Thermal stress

	Single tube	Inner tube	Outer tube
Thermal stress (MPa)	71.2	36.2	26.3

2.3 Results and discussion

In PRAISE code, cumulative failure probability is calculated. Fig. 4 shows the probabilities of each tube on SCC and fatigue by thermal transient.

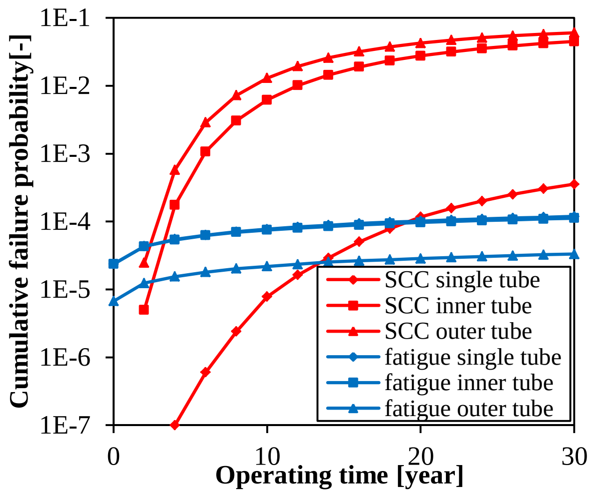

Fig. 4 Cumulative failure probability of each tube

As seen in Fig. 4, about SCC, probability of single tube is lower than that of inner and outer tubes. Major difference in analytical condition involving in SCC between single tube and the other tubes is wall thickness. Accordingly the probability may rise with decrease of wall thickness.

About fatigue by thermal transient, the probability increase in an order of: outer tube, single tube and inner tube. Major differences in analytical conditions involving in fatigue among each tube are wall thickness, thermal stress and pressure difference between outer surface and inner surface of tube. Figure 5 shows the probability of change in the wall thickness under the same conditions of thermal stress and pressure difference. Failure probability of single tube is lower than those of inner and outer tubes because single tube is thicker than the other tubes. Figure 6 shows probability of change in thermal stress and pressure difference under the same condition of wall thickness.

Probability of single tube increases comparing with the other tubes because thermal stress of single tube is larger than that of the others. In addition, the probability of outer tube is lower because pressure difference of outer tube is smaller than that of the others. Accordingly, it is considered that differences of failure probability depend on wall thickness, thermal stress and pressure difference.

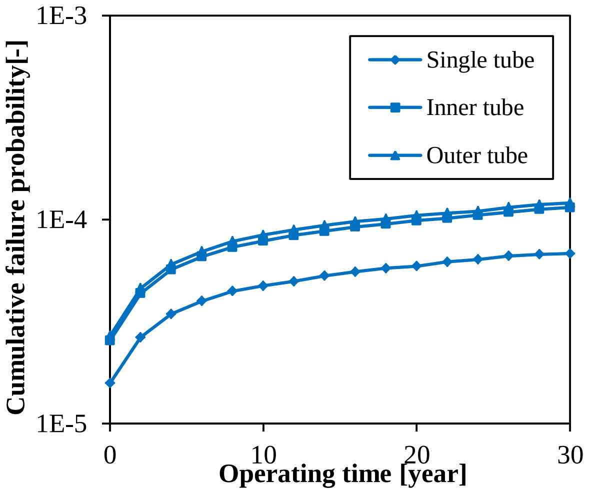

Fig.5 Probability with difference of wall thickness

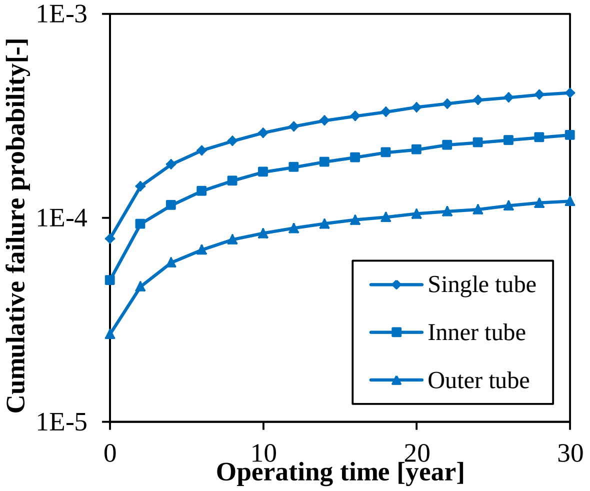

Fig.6 Probability with differences of thermal stress and pressure difference

3. RELIABILITY OF DOUBLE-WALL-TUBE AGAINST SODIUM-WATER REACTION

In this section, probability of sodium-water reaction is evaluated from the results of **2.3** to value the reliability of double-wall-tube system quantitatively. To evaluate through the steam generator, numbers of heat transfer tube and weld parts are considered. It is given that number of tube is around 50, and number of weld parts is 5 per tube.

3.1 Evaluation method

<Single-wall-tube system>

In single-wall-tube system, sodium-water reaction would occur when heat transfer tube is broken. Based on the assumption that SCC and fatigue crack by thermal transient occur independently, probability of the reaction can be evaluated by adding failure probabilities of SCC and fatigue crack.

Probability of single-wall-tube system, P_s, is evaluated by the following equation.

$$P_s = \sum_a P_{s,a} \times 50 \times 5 \quad (7)$$

Here, $P_{s,a}$ is failure probability of single-wall-tube by cause a.

<Double-wall-tube system>

In double-wall-tube system, sodium-water reaction occurs only when inner tube and outer tube which are close to one another are broken at the same time. To evaluate the probability of sodium-water reaction, we classify the scenario of the reaction into independent failure, dependent failure and common cause failure. (Ueda *et al.*, 2000) In the case that inner tube and outer tube are broken simultaneously at different tube, it may take a long time to react. In addition, the amount of reaction decreases because leaked water is scattered in the steam generator. Therefore it is assumed that reaction occurs only when inner tube and outer tube of same heat transfer tube are broken.

(a) Independent failure

Independent failure is defined that both inner tube and outer tube are broken by each different cause for a short period. Fatigue or SCC of inner tube and fatigue of outer tube are assumed to be independent failure causes. Probability of independent failure, P_i, is evaluated by multiplication of each failure probability of inner tube and outer tube. P_i can be evaluated by the following equation.

$$P_i = \sum_a \sum_b P_{in,a} \times P_{out,b} \times 50 \times 5^2 \quad (8)$$

Here, $P_{in,a}$ and $P_{out,b}$ are failure probabilities of inner tube and outer tube by causes a and b.

(b) Dependent failure

In double-wall-tube system, one side tube failure might change the atmosphere around the other tube, and new failure cause would be made. Dependent failure is defined that one side tube is broken by the other side tube failure, and these two failures occur for a short period. In this case, it is considered that failure of inner tube causes SCC of outer tube. Probability of dependent failure, P_d, is evaluated by multiplication of failure probabilities of inner tube for operating time and outer tube for one year. Actually the failure probability of outer tube needed to evaluate P_d is not for one year but for many hours. However in this study, the probability for one year is used to estimate with margin of safety. P_d

is represented by the following equation.

$$P_d = \sum_a \sum_b P_{in,a,t} \times P_{out,b,1} \times 50 \times 5^2 \quad (9)$$

Here, $P_{in,a,t}$ and $P_{out,b,1}$ are failure probability of inner tube for t years and that of outer tube for one year by causes a and b.

(c) Common cause failure

Common cause failure means that inner tube and outer tube are broken by same cause for a short period. SCC of outer tube does not occur when inner tube is under normal operating condition. Therefore fatigue by thermal transient of both tubes is considered as common cause failure.

Probability of common cause failure is evaluated using β factor method. (Mosleh *et al.*, 1998) This method is used with probabilistic safety analysis (PSA). In β factor method, it is considered all failure probability of device is evaluated by summing probabilities of independent failure and common cause failure. β parameter represents rate of common cause failure. When the probability of common cause failure, Pc, between two devices with different failure probabilities is evaluated, different β values depending on the devices are given. P_c is represented by the following equation.

$$P_c = \sum_a P_{in,a} \times \beta_{in} \times 50 \times 5 = \sum_b P_{out,b} \times \beta_{out} \times 50 \times 5 \quad (10)$$

Here, $P_{in,a}$, $P_{out,b}$, β_{in} and β_{out} are probability of inner tube and outer tube by causes a and b, β values of inner tube and outer tube.

Failure causes of these scenarios on double-wall-tube system are shown in Table 4.

Table 4 Failure scenario of double-wall-tube system

	Inner tube	Outer tube
Independent failure	Fatigue/SCC	Fatigue
Dependent failure	Fatigue/SCC	SCC
Common cause failure	Fatigue	Fatigue

The sodium-water reaction probability of double-wall-tube system is evaluated by summing P_i, P_d and P_c.

3.2 Results and discussion

Figure 7 shows reaction probability of single-wall-tube system. It is considered that the fatigue has a dominant influence on the probability until 10 year. Figures 8 and 9 show reaction probability of independent failure and dependent failure. P_i and P_d depend a great deal on SCC because failure probability of SCC is higher than that of fatigue.

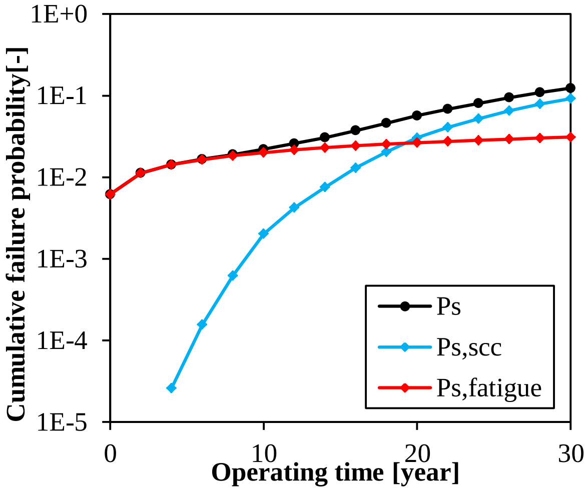

Fig.7 Probability of sodium-water reaction on single-wall tube system

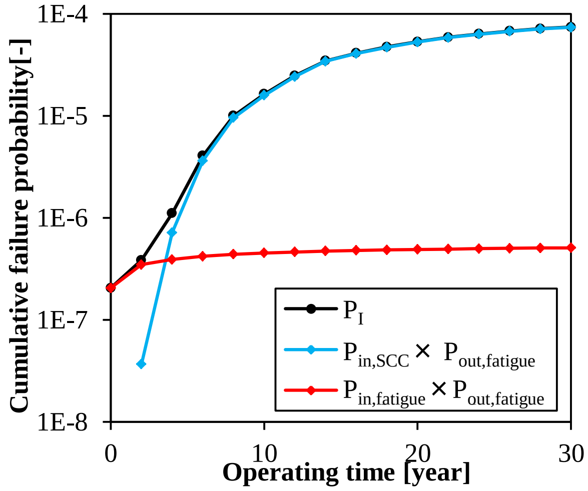

Fig.8 Probability of sodium-water reaction on independent failure

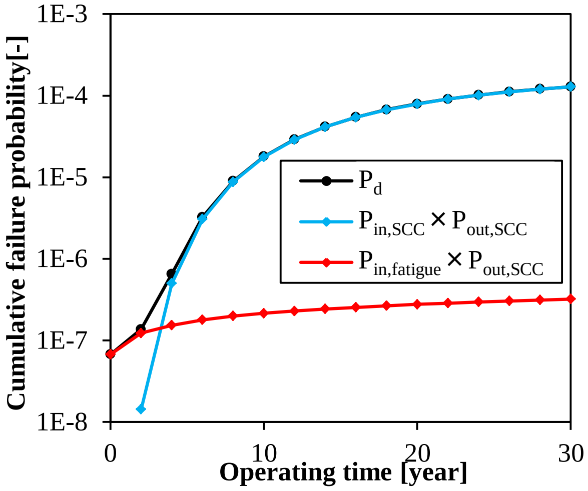

Fig.9 Probability of sodium-water reaction on dependent failure

Figure 10 shows a total reaction probability of single-wall-tube and double-wall-tube system. P_c is calculated with shifting β_{out} from 0.001 to 1.
In this case, the reaction probability of double-wall-tube system is lower than that of single-wall-tube system regardless of β_{out}. It is considered the probabilities between single-wall-tube and double-wall-tube have a big gap because a lot of β values are given from 0.001 to 0.1.

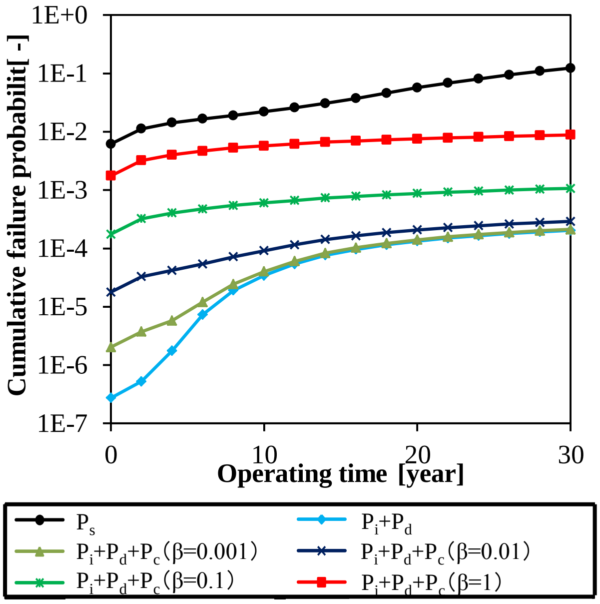

Fig.10 Reaction probability of single-wall-tube and double-wall-tube system

In this study, 304 stainless steel is used as material constant about SCC. However ferrite materials which are selected as material of heat transfer tube have poor sensitivity against SCC. Therefore it is imaginable that P_i and P_d get lower. In addition, only SCC and fatigue by thermal transient due to start-stop operation are considered as crack causes. By including other dominant causes, accurate reliability can be evaluated quantitatively.

4. CONCLUSION

We calculated failure probabilities of single-wall-tube, inner and outer tube of double-wall-tube using PRAISE code in which the probabilistic fracture mechanics (PFM) method is taken into account. From the failure probabilities, reliability of double-wall-tube against sodium-water reaction is evaluated comparing with single-wall-tube.
From the failure probability calculation, it is considered that wall thickness influences the probability about SCC, and that wall thickness, thermal stress and pressure difference between outer surface and inner surface of tube do the probability about fatigue by thermal transient due to start-stop operation.
We classified process that sodium-water reaction occurs at double-wall-tube system into independent failure, dependent failure and common cause failure.
As a result of reliability evaluation, it is represented that probability of sodium-water reaction of double-wall-tube is smaller than that of single-wall-tube in this case. By including other dominant causes, accurate reliability can be evaluated quantitatively.
It is concluded that the present evaluation method has a potential to investigate reliability of double-wall-tube system comparing with single-wall-tube system by calculating failure probability about dominant failure causes of transfer heat tube.

NOMENCLATURE

D	Function related with crack initiation	[-]
f_1	Function of sensitization of material	[-]
f_2	Function of environment	[-]
f_3	Function of strain rate	[-]
t	Time	[year]
a	Crack length in direction	[mm]
b	Crack length in direction	[mm]
$C_i(i=1\sim4)$	Material constant	[-]
K	Stress intensity factor	[ksi in$^{1/2}$]
ΔK	K_{max}-K_{min}	[ksi in$^{1/2}$]
R	K_{min}/K_{max}	[-]
C	Constant in the crack growth law	[-]
m	Exponent for fatigue crack growth equation	[-]
σ	Thermal stress	[MPa]
α	Linear expansion coefficient	[1/K]
E	Young's modulus	[MPa]
r	Length in radial direction	[inch]
ν	Poisson ratio	[-]
T	Temperature	[K]
T_1	Outside surface temperature	[K]
T_2	Inside surface temperature	[K]
P	Probability	[-]
β	β parameter	[-]

Subscripts

min	Minimum
max	Max
o	Threshold
z	Axial direction
r	Radial direction
in	Inner tube
out	Outer tube
s	Single tube
a	Cause
b	Cause
i	Independent failure
d	Dependent failure
c	Common cause failure

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