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CONSTRUCTION OF HIERACHICAL MODEL BASED ON FACTOR ANALYSIS FOR WASTAGE RATE PREDICTION IN SODIUM-WATER REACTION

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ABSTRACT

In a steam generator of a sodium cooled fast reactor, deterioration of the neighbor tubes may happen due to a wastage phenomena when a sodium-water-reaction jet touches the neighbor tubes caused by a leakage of water into sodium. Therefore, there are so many parameters in the phenomenon. Those parameters interact with each other complicatedly, and it is necessary to understand the influence of those parameters and to evaluate the correlations between the parameters in order to investigate the wastage phenomenon. Finally, it is important to predict the wastage rate. In the present study, we analyze the correlations using the DEMATEL method and coordinate a correlation chart of the parameters and construct a hierarchical model based on the factor analysis for the wastage rate prediction in a sodium-water reaction.

1. INTRODUCTION

In a steam generator (SG) of a sodium cooled fast reactor (SFR), both sodium and water exist and are separated with a thin heat-transfer tube. Once the heat transfer tube fails, water leaks into liquid sodium and a sodium-water-reaction (SWR) happens. Since, a secondary tube failure may take place because of a wastage phenomenon where the tube surface is damaged by an erosive and corrosive action caused by the reaction jet, and it is important to predict the wastage phenomenon quantitatively from the viewpoints of safety and economical efficiency of SWR.

For this purpose, the predictions of the wastage rate have been developed in the previous works. However, those are derived based on the characteristic values such as sodium temperature, water leak rate and so on. Accordingly, those correlations include a large uncertainty because the wastage rate is directly affected by the local values near the target tube surface.

In the present paper, a sensitivity analysis of the elemental factors in the SWR has been carried out based on the DEMATEL method to make clear a relationship among factors. Those are classified into 3 categories; cause factors, effect factor and intermediate factors. The cause factors are temperature of sodium, water pressure, leakage diameter and so on. The intermediate factors are temperature of the SWR jet, velocity of SWR jet, and so on. The effect factor is wastage rate. The intermediate factors are local values and cannot be observed in the SWR experiments.

The local values can be obtained by the SWR simulation, using a SWR numerical analysis code SERAPHIM. It was constructed by Takata,T. et al.(2009). And all database included the intermediate factors can be quantified.

Next, we constructed two response surface models about the quantification of the wastage rate. One is constructed with the effect factor and the cause factors, the other is constructed with the effect factor and the intermediate factors. The former is evaluated by the bulk values, and the latter is evaluated by the local values. In this way, we can compare which is better expression to predict the wastage rate.

2. FACTORICAL ANALYSIS OF WASTAGE PHENOMENON

2.1 Analysis of Correlations

First, we coordinated a correlation chart about the wastage phenomenon in order to analyze the correlations of the factors of the wastage phenomena.

2.1.1 Correlations of Groups

Each factor is divided to six groups; a wastage, a target tube, a sodium-water reaction (the reaction jet), a leakage water, sodium, a rapture pipe and water flow in a rapture pipe.

A correlation chart of those groups is showing in Fig.1.

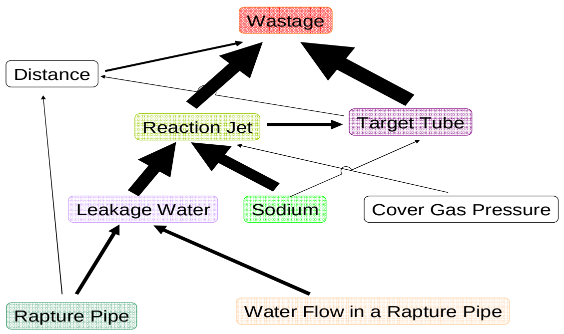

Fig. 1 Correlation Chart of Groups

Figure 1 shows that the wastage is affected by mainly the target tube, and the target tube is affected by mainly the reaction jet. The reaction jet is affected by the leakage water and sodium, and the leakage water is affected by the rapture pipe and water flow in a rapture pipe.

2.1.2 Correlation Chart around each Group

Next, the factors of the wastage phenomenon are subdivided to the groups and we constructed some correlation charts between the factors. Fig. 2, Fig. 3 and Fig. 4 show the correlations of the factors. Fig. 2 shows the correlations between the wastage, the target tube and the reaction jet. Fig. 3 shows the correlations between the reaction jet, sodium and the leakage water. Fig. 4 shows the correlations between the leakage water, sodium, the rapture pipe and water flow in a rapture pipe.

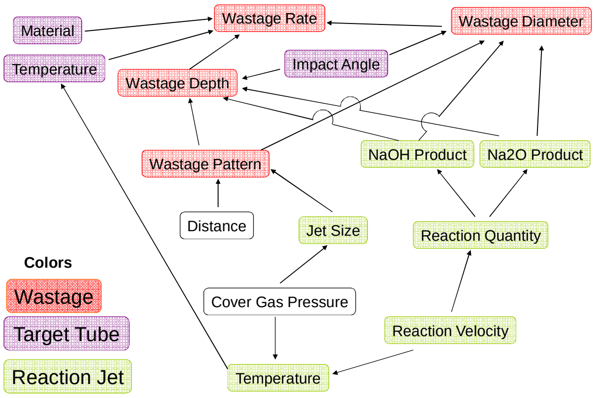

Fig. 2 Correlation Chart around Wastage

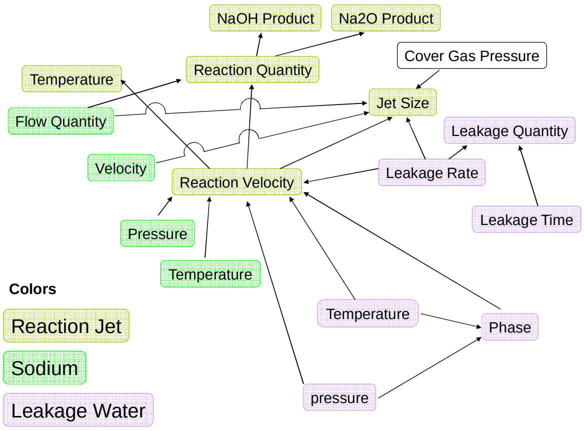

Fig. 3 Correlation Chart around Reaction Jet

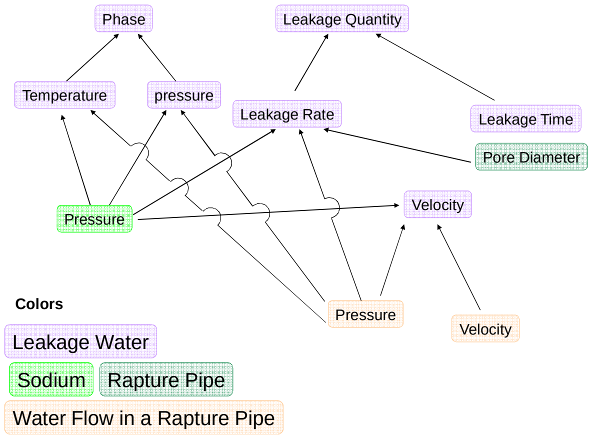

Fig. 4 Correlation Chart around Leakage Water

By matching these figures, a total wastage correlation chart could be constructed.

2.2 Influence Evaluation with DEMATEL Method

We made an adjacency matrix of described above correlation charts. This is shown in Table 1. The standard of influence quantification is based on some experiment data and some simulation data. We applied a DEMATEL (DEcision MAking Trial and Evaluation Laboratory) method for this matrix. The DEMATEL method is a way of extracting parameters which are the large centrality parameters and the large influence parameters. It is usually used for social science field such as Fukui,M. et al.(2007).

First, we standardized the adjacency matrix by the total of column influence.

$$\boldsymbol{X} = \frac{1}{25}\boldsymbol{X}^* \qquad (1)$$

In this experience, $\boldsymbol{X}$ is a direct influence matrix and $\boldsymbol{X*}$ is the adjacency matrix.

Second, we calculated an infinite series of the standardized matrix.

$$\boldsymbol{Y} = \boldsymbol{X} + \boldsymbol{X}^2 + \boldsymbol{X}^3 + \cdots \qquad (2)$$

$\boldsymbol{Y}$ is a total influence matrix.

At last, calculate the sum of row of $\boldsymbol{Y}$ and the sum of sequence. The former is R and the latter is D. We made an influence-centrality graph with (D+R) on the

Table 1 Adjacency Matrix

		b			w				s			j						t			Sur	W				D^*
		P	V	S	T	Voic	P	G	T	P	V	Q	na	n2	T	V	L	T	A	M	L	r	d	p	a	
Burst Tube	Water Pressure	0	0	0	1	0	4	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11
	Water Velocity	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	Leakage Area	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	10
Leakage Water	Temperature	0	0	0	0	6	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	15
	Void Rate	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2
	Pressure	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
	Leakage Rate	0	0	0	0	0	0	0	0	0	0	4	0	0	0	9	9	0	0	0	0	0	0	0	0	22
Sodium	Temperature	0	0	0	6	0	0	0	0	0	0	0	0	0	9	0	0	9	0	0	0	0	0	0	0	24
	Pressure(Cover Gas Pressure)	0	0	0	0	0	0	6	0	0	0	0	0	0	0	8	0	0	0	0	0	0	0	0	0	14
	Velocity	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2
Sodium-Water-Reaction	Reaction Amount	0	0	0	0	0	0	0	0	0	0	0	9	9	7	0	0	0	0	0	0	0	0	0	0	25
	Production of NaOH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	6	8
	Production of Na2O	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	2	8
	Temperature	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	9
	Velocity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	6	0	0	15
	Largeness	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	9	0	10
Target Tube	Temperature	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	9
	Angle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	9	16
	Material	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	9
Surrounding	Length	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	9	0	18
Wastage	Rate	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Depth	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	2
	Pattern	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	9	18
	Area	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	2
	R^*	0	0	0	7	12	4	22	0	0	0	8	9	9	25	17	9	27	2	0	0	31	30	18	26	

abscissa and (D-R) on the ordinate. This is shown in Fig. 5.

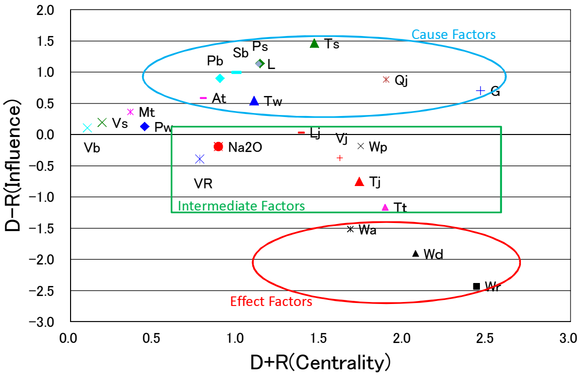

Fig. 5 Influence-Centrality

In this figure, the factors at right side have the large centrality, the factors in upside are the cause factors and the downside factors are effect factors.

2.3 Hierarchization of Factors of Wastage Phenomenon

We could stratify some dominant factors of the wastage phenomenon with Fig. 5. From this, the cause factors are the temperature of sodium and water, the leakage rate, the leakage diameter, the distance and so on. The intermediate factors are the temperature of jet and target tube, the wastage pattern, velocity of jet, the largeness of jet and so on. The effect factors are the wastage rate, the wastage depth and the wastage area.

3. DEVELOPMENT OF WASTAGE PREDICTION MODEL

3.1 Data Imputation with Numerical Simulation

The intermediate factors classified in 2.3 such as the temperature of SWR jet, the temperature of the target tube, velocity of SWR jet and the wastage pattern cannot be observed in the wastage experiment. So, we simulated a SWR with a SWR analysis code “SERAPHIM” in order to fill their data.

The conditions of the numerical simulation are based on a SWR experiment on SWAT-1R in Japan Atomic

Table 2 Conditions and Results from Experiments

Run-No.	TW1-1	TW1-2	TW1-3	TW1-4	TW1-5	TW1-6	TW2-1	TW2-2	TW2-3	TW2-4	TW2-5	TW2-6
Material	12Cr											
Spacing to Target(mm)	16.2											
Temperature of Water(K)	753											
Pressure of Water(MPa)	13											
Temperature of Sodium(K)	753											
Pressure of Cover Gas(MPa)	0.13											
Leakage Diameter(mm)	0.4	0.4	1.0	1.0	1.2	1.2	0.3	0.3	0.3	0.3	0.7	1.0
Leakage Rate(g/s)	6.79	8.53	5.36	9.61	9.49	13.49	1.89	1.98	3.77	3.53	16.15	15.22
Wastage Rate(10^-2mm/s)	4.20	6.52	3.36	3.56	5.02	4.90	1.67	1.86	3.33	3.66	4.41	5.31

Energy Agency (JAEA). It was made by Shimoyama,H.(2004).

We indicate the conditions and the results from experiments on SWAT-1R in JAEA. So, a parameter of numerical simulation is the leakage diameter.

3.1.1 Temperature of SWR Jet Adjacent Tube

We indicate the change of the temperature of SWR jet adjacent target tube in Fig. 6~11.

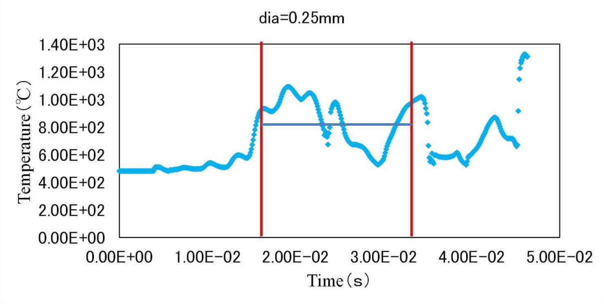

Fig. 6 Temperature of SWR Jet Adjacent Tube at D=0.25mm

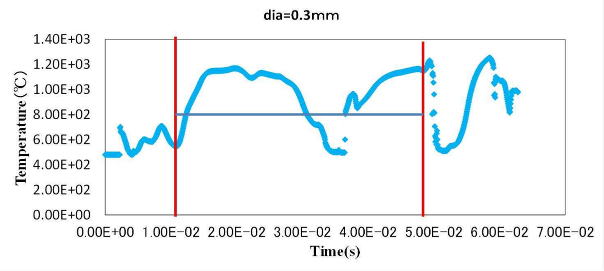

Fig. 7 Temperature of SWR Jet Adjacent Tube at D=0.3mm

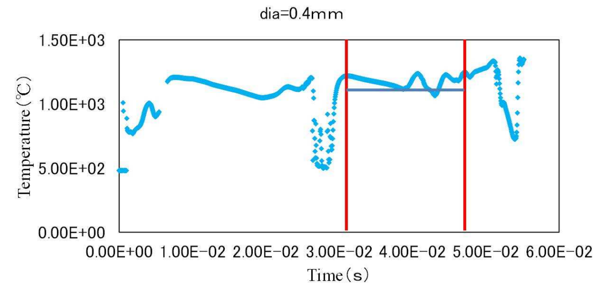

Fig. 8 Temperature of SWR Jet Adjacent Tube at D=0.4mm

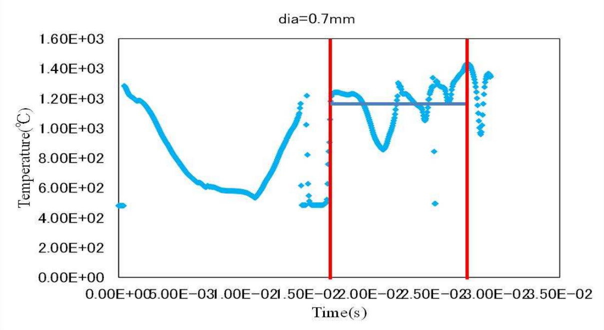

Fig. 9 Temperature of SWR Jet Adjacent Tube at D=0.7mm

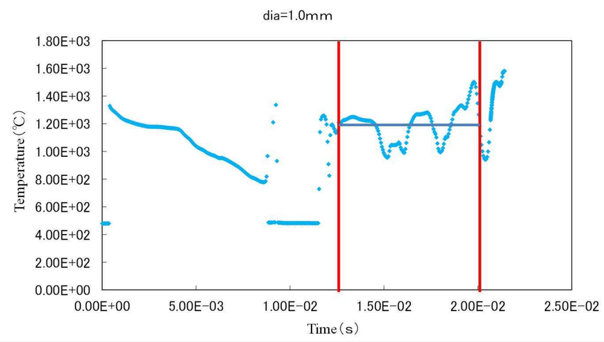

Fig. 10 Temperature of SWR Jet Adjacent Tube at D=1.0mm

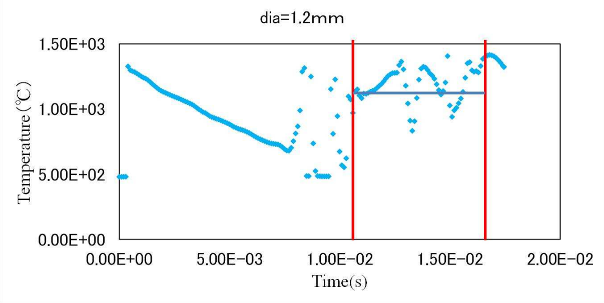

Fig. 11 Temperature of SWR Jet Adjacent Tube at D=1.2mm

From these figures, we determined some characteristic temperature of the SWR Jet adjacent the target tube. The areas surrounded two red lines in these figures are the steady-state of the leakage rate. We indicate the characteristic temperature in Table 3.

Table 3 Characteristic Temperature of the SWR Jet Adjacent Tube

D(mm)	Tt(℃)	Tt(K)
0.25	800	1073
0.3	820	1093
0.4	1180	1453
0.7	1190	1463
1	1150	1423
1.2	1210	1483

3.1.2 Velocity of the SWR Jet

We obtained the data about velocity of the SWR Jet adjacent the dtarget tube from the numerical SWR simulation. It is shown in Table 4.

Table 4 Velocity of SWR Jet

D(mm)	Vj(m/s)
0.25	25
0.3	40
0.4	85
0.7	160
1.0	180
1.2	210

3.1.3 Comparison Leakage Rate

The difference in pressure between water and sodium is so large that the leakage velocity is very fast. The limitation is the sonic velocity and the leakage velocity cannot be over the sonic speed. We made a study on a consistency of the experiment and the numerical simulation by comparison the leakage rate of the experiment, of the numerical simulation and of the sonic velocity. We indicate a figure of comparison the leakage rate in Fig. 12.

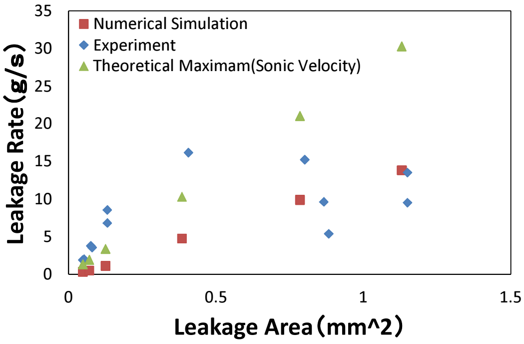

Fig. 12 Comparison Leakage Rate

From this figure, it is shown that the leakage rate of the experiment is larger than one of the sonic velocity in small leakage area, and it is contradictory. So, although the leakage rate is selected for the cause factors in 2.3, we would like to use a leakage area as a cause factor parameter. The leakage area is a reliable parameter and a dominant factor for the leakage rate.

3.2 Hierarchical Model

In this section, we construct two models; a non-hierarchical model and a hierarchical model. The non-hierarchical model is the traditional model.

First, we indicate the non-hierarchical model based on the only experiment data. It was constructed by Usami,M. et al.(1988) and Nei,H. et al.(1974). The wastage rate was used for the effect factor. The area of leakage area and temperature of sodium was used for the caused factors.

$$Wr = A_1 exp\left\{-A_2\left(ln\frac{S}{A_3}\right)^2 - \frac{A_4}{T_s}\right\} \tag{3}$$

A1	5.353
A2	0.191
A3	0.339
A4	4.989

Next, we indicate a hierarchical model based on 2.3. We used the leakage area and temperature of sodium as the cause factors, velocity of SWR jet adjacent the target tube and temperature of SWR jet adjacent the target tube as the intermediate factors.

$$Wr = A_1 exp\left\{-A_2\left(ln\frac{Vj}{A_3}\right)^2 - \frac{A_4}{T_t}\right\} \tag{4}$$

A1	2.690E+01
A2	1.089E−04
A3	8.442E+00
A4	2.568E+03

$$V_j = A_1\sqrt{S} \tag{5}$$

A1	1.982E−01

$$T_t = \llbracket 1440, T_s + A_1 S \rrbracket$$
$$\llbracket A, B \rrbracket means\ select\ a\ samller\ parameter \tag{6}$$

A1	6870

Equation (5) is derived from Fig. 13.

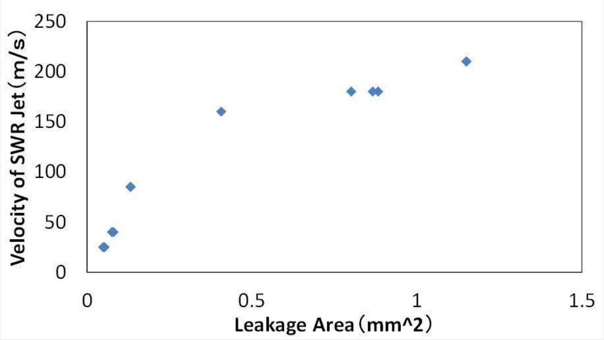

Fig. 13 Relation among Velocity of SWR Jet-Leakage Area

Equation (6) is derived from Fig. 14.

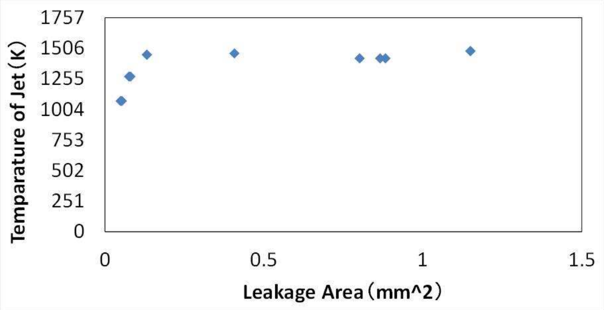

Fig. 14 Relation among Temperature of SWR Jet-Leakage Area

3.3 Results and Discussions

We indicate the results of the wastage rate prediction from these evaluation equations in Fig. 15 and Table 5.

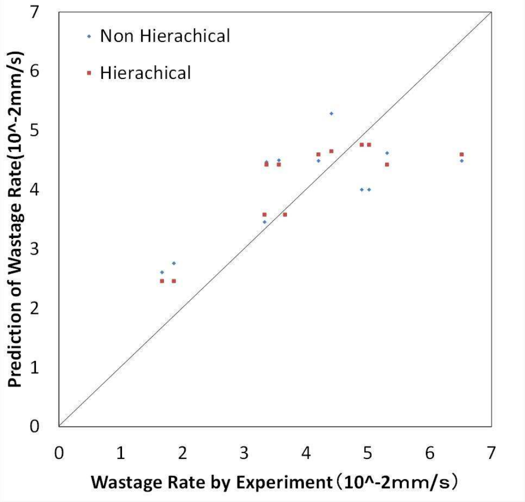

Fig. 15 Wastage Rate Prediction

Table 5 Residual Sum of Squares and Variance

	Residual Sum of Squares	DOF	Variance
Non Hierarchical	1.111E+01	8	1.1784
Hierarchical	7.719E+00	8	0.9823

Figure 15 and Table 5 show that there is just a little improvement. We can list some conceivable reasons occurring such results below.

First, as shown in Table 2, the numerical simulation in this present study is just a small leakage rate and the equations (4) ~ (6) are based on this scope. There is a possibility that the relation among the cause factors and the intermediate factors is just constructed in a limited way.

Next, temperature of sodium in this experiment used for this numerical simulation in the present study is not used for as a parameter, so equation (3) is not corresponding to the change of temperature of sodium. Thus, Fig. 14 shows that temperature of the target tube is constant over 0.2mm^2 of leakage scope. So, probably, it may be that the hierarchical model is not reflected the effect of addition intermediate factors.

From these results, it can be said that hierarchization of the wastage rate prediction model is a good way based on a premise of construction a better model between the cause factors and the intermediate factors by numerical simulation in other conditions. In addition, more data imputation can makes that we can select more factors and the prediction precision would get better.

However, there is a room of examination how we observe and calculate the leakage rate in the SWR experiments.

4. CONCLUSIONS

In the present study, we analyzed the factors related to the wastage phenomenon. Each factor is classified into the cause factors, the intermediate factors and the effect factors. And the factors could be hierarchized.

The intermediate factors cannot be observed in the experiment of the wastage phenomenon. So, we simulated the SWR in order to carry out the intermediate factors data imputation.

Finally, we constructed a hierarchical model for wastage prediction model with the large centrality factors based on the DEMATEL method. As a result, the prediction precision for the wastage rate is improvement a little. From these results, it could be said that this method is a good way to predict the wastage rate.

From this study, the future tasks to predict the wastage rate are two points. One is that we need more data imputation by the experiments and the numerical simulations. And the other is that how we observe and calculate the leakage rate in experiments.

ACKNOWLEDGEMENTS

This study is based on SWAT-1R experiments and SERAPHIM numerical simulation. We wish to acknowledge Dr. Ohshima belonged to JAEA.

NOMENCLATURE

P	pressure	[Pa]
V	velocity	[m/s]
D	leakage diameter	[mm]
S	leakage area	[mm^2]
T	temperature	[K]
VR	void rate	[-]
G	leakage rate	[g/s]
Q	reaction amount	[mol]
L	distance from leakage to target tube	[mm]
A	angle	[rad]
Wr	wastage rate	[10^{-2}mm/s]
Wd	wastage depth	[mm]
Wp	wastage pattern	[-]
Wa	wastage area	[mm^2]

Subscripts

b	burst tube
w	leakage water
s	sodium
j	SWR jet
t	target tube

REFERENCES

Fukui,M. et al.(2007). “Multi-purpose Program for Social System Analysis 9 - Dematel, Social Decision Making, Other Reinforcements -” Fukuyama Heisei University

Nei,H. et al.(1974).”Studies of Small Leak Sodium-Water Reactions(4) Steam Wastage and Responses of Leak Detectors” SN941 74-45 O-arai Engineering Center

Okuno,T. et al.(2011).” Sensitivity Study on Elemental Factors of Wastage Phenomena”J40, SESJ

Shimoyama,H.(2004)“Wastage-Resistant Characteristics of 12Cr Steel Tube Material”. JNC TN9410 2004-009 O-arai Engineering Center

Takata,T. et al.(2009), "Computational Methodology of Sodium-Water Reaction Phenomenon in Steam Generator of Sodium-Cooled Fast Reactor” J. of Nucl. Sci. and Tech., Vol.46, No.6, pp.613-623

Usami,M. et al.(1988).”Wastage Properties of High-Chrome Steels as Heat Transfer Tube Material for Steam Generator(Small Leak Wastage Tests)” PNC SN9410 88-129 O-arai Engineering Center

Yamaguchi,T.(2010).”Estimation of Wastage phenomena in sodium-water reaction using Bayesian network” J5 Osaka-university