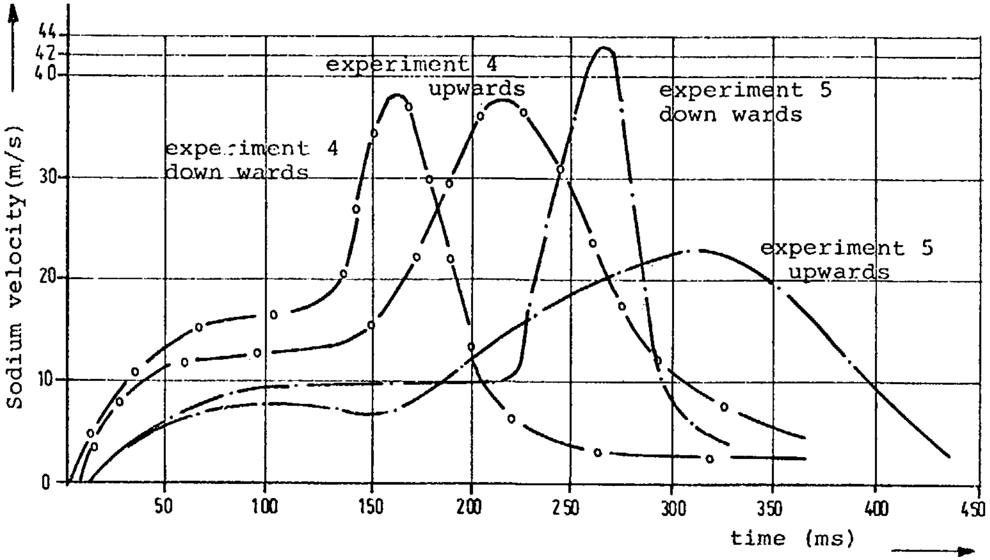

Figure 11: Sodium velocities (direct blow down)

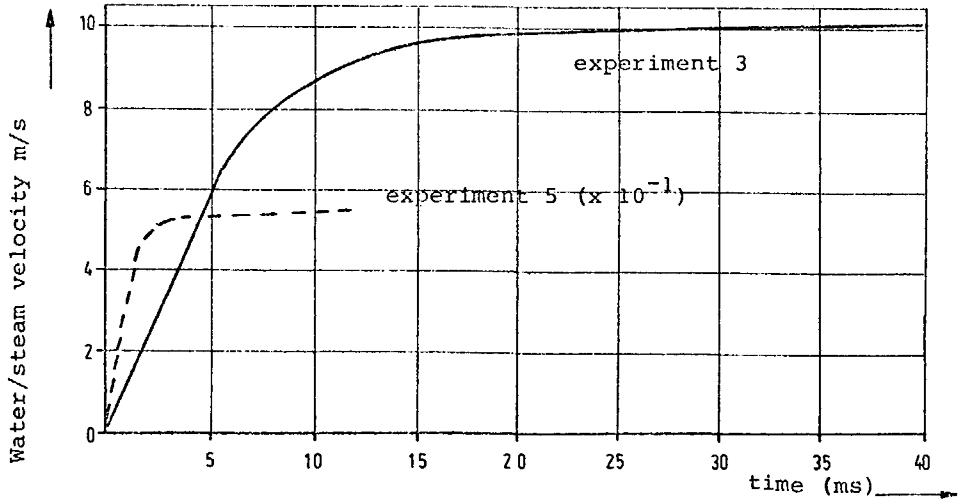

Figure 12: injection velocity

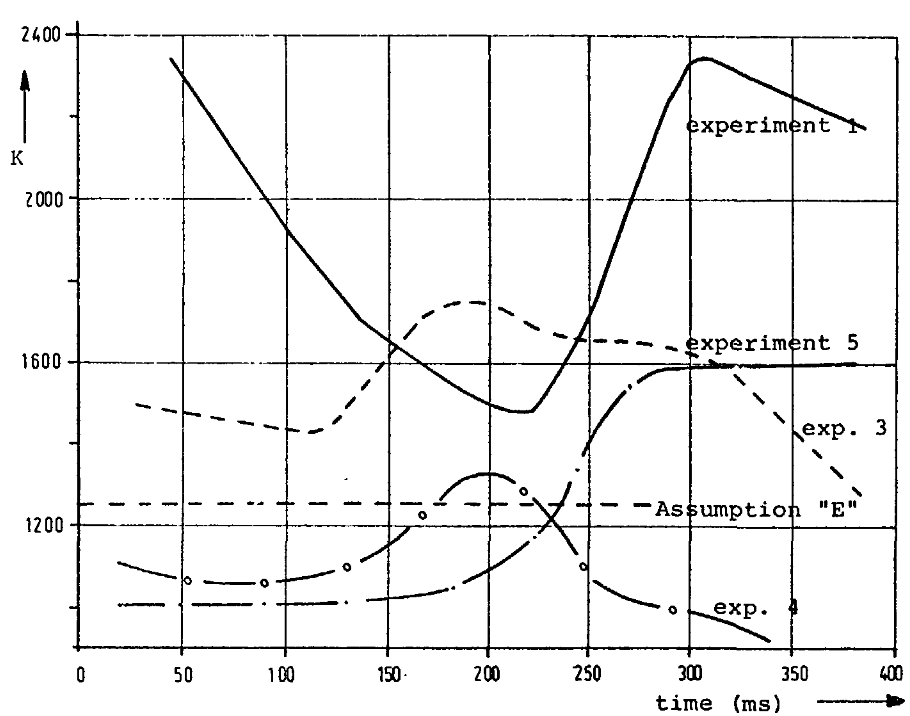

Figure 13: Calculated reaction zone temperatures

C.3. Large-Leak Sodium-Water Reaction Analysis for Steam Generators

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ABSTRACT

The guillotine rupture of 4 tubes is assumed as a design basis regarding the large-leak sodium-water reaction in the system of the MONJU steam generator.

Three kinds of analyses were performed with the view to showing the integrity of the steam generator system on the reaction. The first one is the analysis of the initial pressure spike, assuming the initial guillotine rupture of 1 tube. The analysis was performed by utilizing one-dimensional sphere-cylinder model code SWAC-7 and two-dimensional axisymmetric code PISCES 2DL. The second one is the analysis of the secondary peak pressure and its propagation in the system, assuming the instantaneous guillotine rupture of 4 tubes. The third one is the analysis of the dynamic deformation of the steam generator shell.

The integrity of the steam generator system was shown by the analyses.

1. INTRODUCTION

MONJU, the proto-type FBR, requires a technically sound design to prevent the tube failure. The design includes the selection of suitable materials, improvement of thermal and hydraulic characteristics, reliable structures of tubes and tube-supports with an adequate torelance for thermal stress and vibration, inspectability of tubes, and quality assurance of welds.

In the event of the small leak which could occur despite the care taken during design, construction and operation, the secondary failure is prevented by the system of the leak detection and water/ steam discharge.

Against the consequences of unlikely occurrence of the large-leak sodium-water reaction, the plant, its operating staff and IHX are protected by the relief system and the adequate strength of the system. The guillotine rupture of 4 tubes is specified as a basis of design.

The present report describes analytical studies on the large leak sodium-water reaction in the system of the MONJU steam generator. Because the instantaneous rupture of 4 tubes is extremely unlikely and unexpected, it is assumed that one initial rupture occurs with three consecutive ruptures. This accident results in initial pressure spikes and the secondary pressure peaks as the consequences of the chemical reaction between a large amount of water and sodium. The steam generator system should withstand the pressure. The analyses are performed on the initial pressure spike, the secondary pressure peak and the dynamic strength of the steam generator shell.

The calculation model of the secondary sodium system and steam generator are shown in Fig. 1 and Fig. 2 respectively. The evaporator, superheater and reheater are of the same concept, that is, the straight tube type with the sine-wave bends at the lower part.

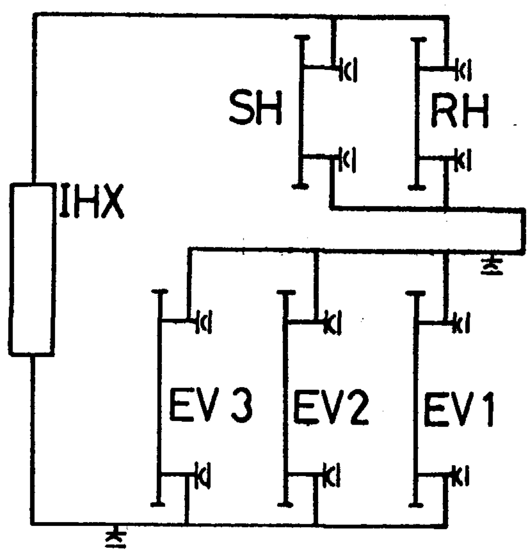
2. PRESSURE ANALYSIS

2.1 Initial Pressure Spike

The initial pressure spike has a high peak pressure and a short peak duration. The peak duration is so short that neither relief system nor free surface can decrease its impulsive effect. For this reason, the initial pressure spike itself has to be studied with the view to estimating the integrity of the steam generator.

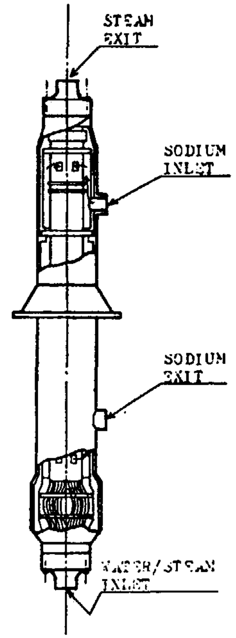
Experiment

A series of experiments using SWAT-1 rig of PNC is performed with the view to obtaining information on the initial pressure spike[1)2)] The data show the effects of water pressure, rupture size and set pressure of the rupture disk installed at the hole of a water injection. Because the correlations among these effects are complex, only the correlation between the peak pressure and duration of the experiments[2)] are shown in Fig. 3. From this figure, it is seen that the data has the same tendency. The peak pressure decreases violently near 1 ms of the peak duration. The data of ESADA[3)] are shown in Fig. 4. Fig. 4 shows the same tendency as Fig. 3.



Model of the secondary sodium system

Fig. 1



Concept of the steam generator

Fig. 2

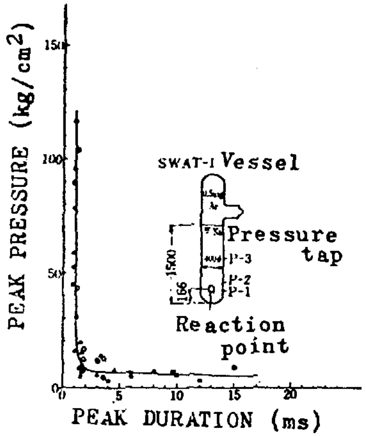


Fig. 3 PNC data of the initial pressure spike

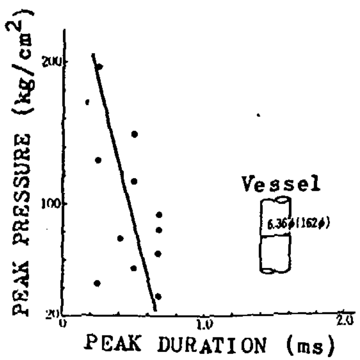


Fig. 4 ESADA data of the initial pressure spike

The peak duration of ESADA is shorter than 0.7 ms. The data of INTERATOM also show the initial pressure spike[4].

From these figures, it is seen that there might be a violent reaction and a calm reaction depending on the initial state of sodium and water. The violent reaction results in the initial spike with high pressure and short duration while the calm reaction results in the initial spike with low pressure and long duration. The peak pressure is attained in shorter than 0.5 ms for the violent reaction. For this reason, sodium and water can be assumed to complete the reaction in this time.

Analysis of SWAT-1 data

The analysis of SWAT-1 data is performed using SWAC-7 code, the results have been reported already[2]. SWAC-7 code uses one-dimensional sphere-cylinder model that is called the S-C model from now.[2,5] The results of the S-C model are compared with two-dimensional axisymmetric results obtained by PISCES 2DL code[6] as follows. The conditions of PO4 experiment of SWAT-1 are used for the calculation.[2] The concept of the vessel of SWAT-1 is shown in Fig. 3. The initial radius of a reaction bubble is 1 cm. The temperature of the bubble is maintained constant. The pressure of the bubble obtained by the S-C model is used as the boundary condition for the two-dimensional analysis, and shown in Fig. 5 as a function of time.

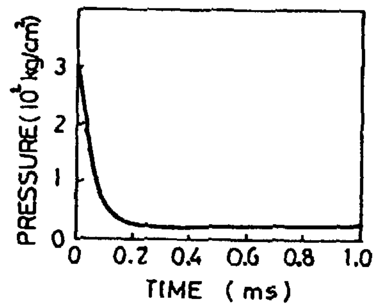
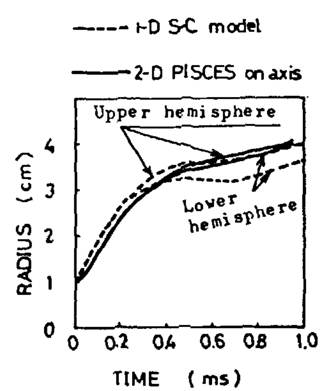


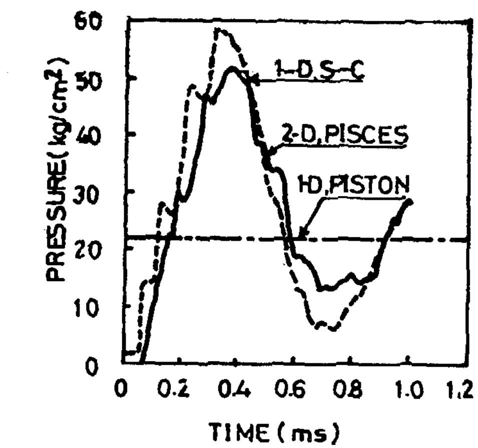
Fig. 5 Time history of reaction products pressure (used as the boundary condition of PISCES 2DL)

Two-dimensional velocity patterns of sodium are shown in Fig. 6, a) through d). From these figures, it is seen that the flow near the bubble is of spherical symmetry while the cylindrical piston flow is far from the bubble. This agrees with the assumption used in the S-C model. The growth of the bubble radius is shown in Fig. 7 as a function of time. The rate of the growth of the S-C model is bigger than that of two-dimensional results. However, the difference is small.



Growth of reaction products bubble

Fig. 7



Time history of SWAT-1 wall pressure

Fig. 8

The pressure at P-1 in Fig. 3 is shown in Fig. 8 as a function of time. The two-dimensional analysis results in lower pressure than the S-C model. The result of one-dimensional piston model is also shown in Fig. 8. The piston model does not show the charac-

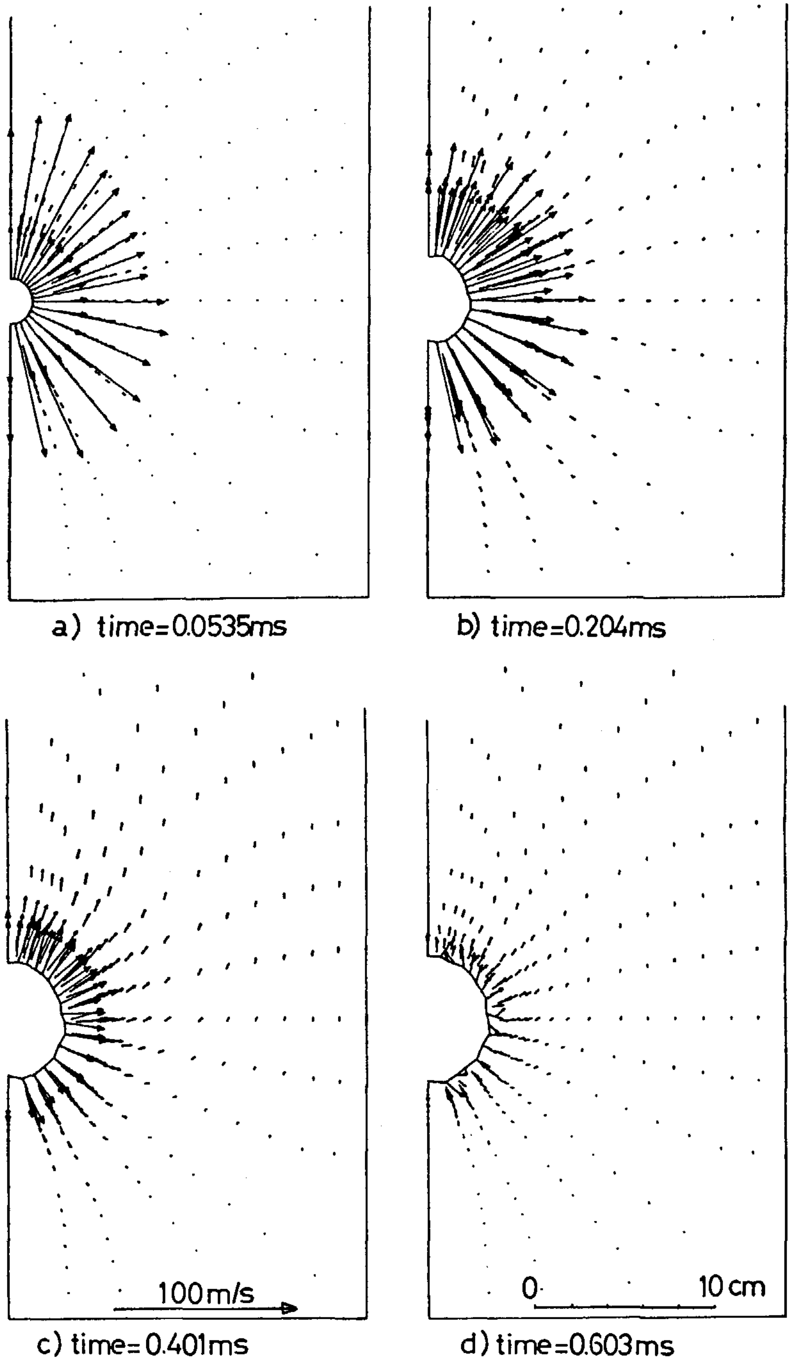


Fig. 6 Two-dimensional flow pattern of sodium in SWAT-1

teristics of a spike and results in the lowest pressure among three models. The piston model approximates the phenomena after 1 ms.

Analysis of steam generators

Based on the results described above, we conclude that the S-C model can be used economically to predict the initial pressure spike. The following assumptions were used conservatively to calculate the initial pressure spike in the steam generators.

i) The guillotine rupture of 1 tube is assumed.

ii) Water leaked in 0.5 ms occupies the same volume in sodium as in the tube.

iii) The amount of water described above reacts with sodium adiabatically at constant volume under the following change.

$$2Na + H_2O \longrightarrow Na_2O + H_2$$

Pressure, temperature and volume on the equilibrium are used as the initial condition of a reacting bubble.

iv) The bubble expands at constant temperature.

The conditions and results of the analysis are shown in Table 1. The peak pressure and duration are about 100 kg/cm^2g and 1 ms, respectively.

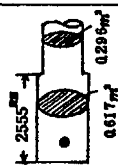
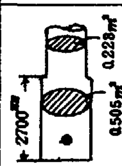
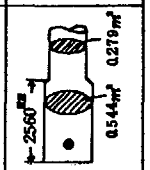
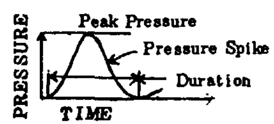
	Unit	EV	SH	RH
Reaction Pressure	kg/cm^2g	2150.	620.	104.
Temperature	^oK	1900.	2310.	2450.
Volume	cm^3	5.5	24.3	160.
Water mass	g	1.33	1.40	1.50
Sonic velocity	m/s	1945.	1840.	1858.
Geometry Black point is reaction products				
Results				
Peak pressure	kg/cm^2g	96.	95.	54.
Duration	ms	0.9	0.9	1.2
Definition				

Table 1 Initial pressure spikes of steam generators

2.2 Secondary Pressure Peak

After the decay of the initial pressure spike, the secondary pressure peak is attained by increase of leak rate of water. The radius of the bubble is large enough to use the one-dimensional piston model when the secondary pressure begins to increase. The analyses of the secondary pressure peak and its propagation were performed for the system and steam generator shown in Fig. 1 and Fig. 2. One-dimensional SOWACS code[7] was used. The following assumptions were used conservatively.

i) The guillotine rupture of four tubes occurs instantaneously.

ii) Chemical change is the same one as assumed for the analysis of the initial pressure spike.

iii) Reaction temperature is constant and equal to the evaporation temperature of sodium oxide, 1,350 °C.

The rupture disk is assumed to open perfectly at the moment when the pressure reaches its set pressure. This results in the lower pressure than the actual one for several milliseconds.

The secondary pressure peak of the failed evaporator is shown in Fig. 9.

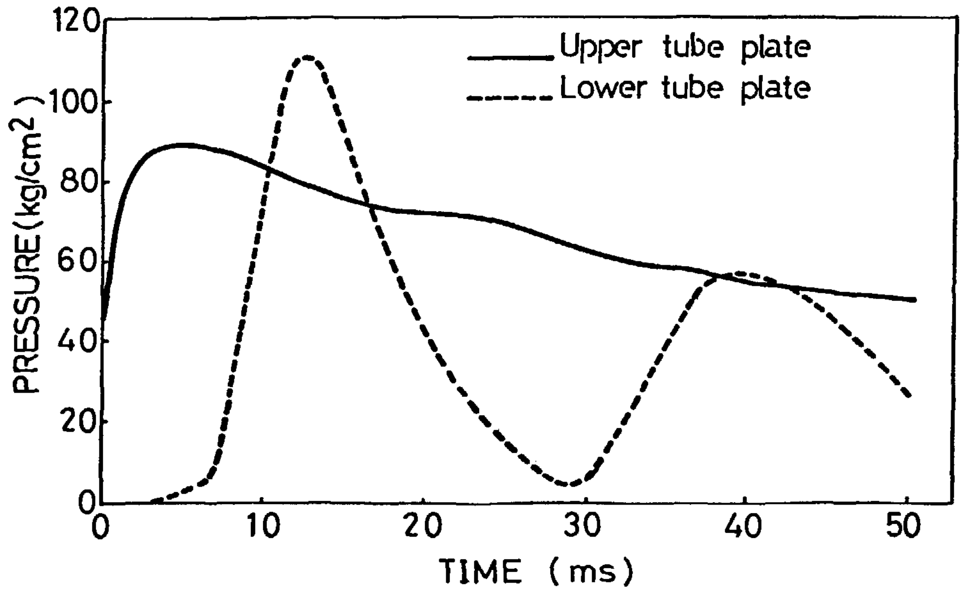


Fig. 9 Secondary pressure peak of failed evaporator

The rupture point is under the upper tube-plate of the evaporator in Fig. 2. From this figure, it is seen that the pressure is higher at the lower tube-plate than upper one, and that the pressure of the lower tube-plate is oscillating by frequency of 40 Hz with damping. These are resulted from the reflection of a pressure wave. These phenomena has to be considered in the design. The maximum pressure attained at every place of the system is shown in Table 2. The pressure propagated from the failed steam generator to the system is satisfactorily lowered by the relief system.

Place of system \ Rupture point			EV No. 1 Upper Tube-plate	EV No. 3 Upper Tube-plate	SH Upper Tube-plate	SH Lower Tube-plate	RH
SG Bank	Failed SG	Rupture point	87	87	44	45	34
		Maximum point	109	110	47	45	43
	Adjacent SG	EV	17	20	2	3	3
		SH	6	5			8
		RH	6	5	8	2	
2ndary Sodium System	Hot leg		6	5	6	1	6
	Middle leg		6	5	7	10	10
	Cold leg		4	6	3	1	3
	IHX		4	6	3	1	3

EV: Evaporator, SH: Superheater, RH: Reheater (kg/cm^2g)

Table 2 Maximum pressure of the secondary sodium system on the guillotine rupture of 4 tubes

3. DYNAMIC STRENGTH ANALYSIS

As shown above, the large-leak sodium-water reaction results in the high pressure in several milliseconds. For this reason, the strength analysis has to be performed using dynamic model, that is, inertia of structure has to be considered. For this purpose, one-dimensional DYNSHL[8], PISCES 1DL[6] and two-dimensional axisymmetric DANTE[8] code have been used.

Though the maximum pressure described in 2.1 and 2.2 are lower than 110 kg/cm^2g, the feed water pressure 148 kg/cm^2g was used for the calculation of the dynamic strain of the evaporator. The inner diameter of the shell is 1,290 mm and thickness 43.4 mm.

The dynamic strain of the evaporator shell is shown in Fig. 10.

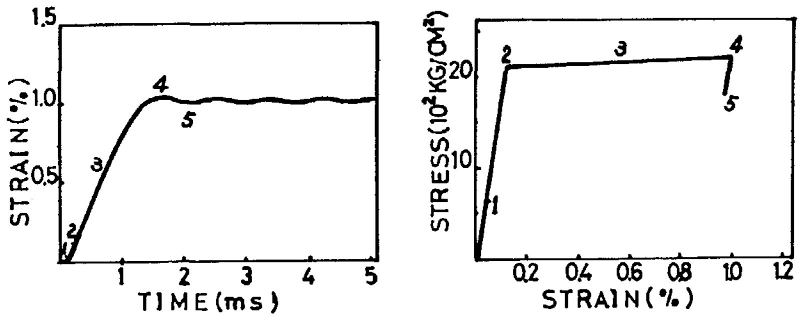


Fig. 10 Dynamic strain of the evaporator shell

The strain is less than 1%. Therefore, the integrity of the shell is assured.

The strain hardening of a 2.25Cr-1Mo steel is so small that the strain increases markedly with the stress. In the present calculation, strain ε and stress σ are

$$\varepsilon = (\text{constant}) \times \sigma^{10}$$

Therefore the margin of pressure or thickness is very important.

The margin is less important for the superheater and reheater than for the evaporator, because the exponent of σ is small for a stainless steel than for a 2.25Cr-1Mo steel. The dynamic strains of the superheater and reheater are also calculated in the same way, obtaining the strain less than 1%.

4. CONCLUSIONS

i) On the guillotine rupture of 4 tubes, the integrity of the steam generator system was shown by the analyses.

ii) One-dimensional S-C model agrees well with two-dimensional axisymmetric model for the analysis of the initial pressure spike.

iii) After the completion of the initial pressure spike, one-dimensional piston model can be used. For the experiment of SWAT-1, the piston model agrees well with the S-C model after 1 ms.

iv) The secondary pressure peak might show oscillation resulted from the reflection of the pressure wave. In the present work, the pressure of the evaporator showed the oscillation of 40 Hz with damping.

v) The dynamic strain increases markedly with the stress. Therefore, the margin of the pressure or the thickness is important.

vi) The strains of the shell of the evaporator, superheater and reheater are less than 1% on the guillotine rupture of 4 tubes.

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