ANALYSES OF HYDRODYNAMIC EFFECTS OF LARGE SODIUM-WATER REACTIONS

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SUMMARY

Large leak sodium-water reactions that would occur in a steam generator of LMFBR causes abrupt changes of pressure and velocity of fluid in a secondary sodium system and relief system. These changes exert unsteady forces on piping and components. The estimation of the effect of the pressure and forces is needed to assess the integrity of the system. SOWACS-III code has been developed to predict the pressure, velocity, flow-induced forces and the response of the piping and components to these forces.

This paper describes SOWACS-III together with its model and method. Results of analyses are also given, the comparison with experimental results of initial pressure spike being included.

SOWACS-III treats the system which consists of the steam generator, vessel, valve, pump and pipe, and uses the following models and methods. (1) Components are assumed to be one-dimensional. (2) Pressure wave propagation near a reaction zone, where hydrogen is generated, is analyzed with the spherical co-ordinate (sphere-cylinder model). (3) A moving boundary is formed by contact of sodium with other fluid such as hydrogen and nitrogen. The boundary travels without mixing of sodium and another fluid through the boundary (boundary tracking model). The boundary can be treated not to move from the original place (fixed boundary model). (4) Pressure wave propagation is analyzed by the explicit method of characteristics in one-dimensional Eulerian co-ordinate. (5) Flow-induced force is analyzed by momentum balance. (6) The lateral motion of relief piping caused by the force is analyzed by NASTRAN code.

Analyses were carried out for large sodium-water reaction experiments in SWAT-3 rig of PNC by using the sphere-cylinder model. The calculated pressure spike in the reaction vessel was compared with the measured one for a few milliseconds after water injection. The calculated value and measured one were 6.4 ata and 6.7 ata for peak pressure and 0.6 ms and 2.8 ms for rising time, respectively.

Velocity and pressure transients in the secondary sodium system and relief system were calculated for the case of simultaneous rupture of four tubes in an evaporator for a proto-type scale LMFBR. Results of boundary tracking model were compared with those of fixed boundary model. The maximum pressure in the evaporator and maximum sodium velocity in the relief piping were 40 ata and 31 m/s for the boundary tracking model and 40 ata and 31 m/s for the fixed boundary model, respectively.

The calculation of stress in the relief piping showed following results. The membrane stress due to internal pressure, bending stress due to flow-induced force and thermal stress due to temperature change were 1.68 kg/mm^2, 11.5 kg/mm^2 and 16.4 kg/mm^2, respectively.

As conclusions, (1) the sphere-cylinder model can simulate the initial pressure spike in the system of SWAT-3 scale, (2) the moving boundary can be approximated by the fixed boundary model that can simplify a computer program and shorten calculation time, (3) the stress due to the flow-induced force would be so high that careful attention is needed for the design of the relief piping.

1. Introduction

In a steam generator for the LMFBR, heat is transfered from sodium to water through the wall of tubes.

If water leaks into sodium through a crack in the wall of the tube, it results in sodium-water reactions. Most of the leak events are anticipated to be small leak. In regard to a large leak event, a common agreement is as follows. "The incident of several water tubes failing simultaneously or within milliseconds of each other, causing double-ended fracture of each tube is unrealistic and the design criterion should be a single tube suffering a double-ended fracture as the initiating event, even accounting for the escalation of small leaks. It is recognized that following the initial event (double-ended tube fracture) there may be additional tube ruptures due to rapid wastage or overheating of these tubes, which will add to the quantity and rate of water injection, which must be considered and allowed for in the design and sizing of the sodium-water reaction pressure relief system [1]."

The phenomena of the large leak sodium-water reaction can be described as follows: A hydrogen bubble of high temperature and pressure is produced. The bubble grows pushing sodium surrounding it. This increases the pressure of sodium in the steam generator. Pressure load is exerted on the steam generator. Rupture disks break due to the increase of pressure in the steam generator. Sodium flows into the relief system. Fluid-induced force begins to exert on the relief piping.

The estimation of the effect of the pressure and forces is needed to assess the integrity of the system. SOWACS-III code has been developed to predict the pressure, velocity, flow-induced forces and the response of the piping and components to these forces.

This paper describes the following regarding SOWACS-III.

(a) Treatment of the secondary sodium system, failed steam generator and relief system.

(b) Evaluation of the model of the failed steam generator
The success of the code depends on the capability of the modeling of the phenomena near a reaction zone. Analyses are carried out for a large sodium-water reaction experiment in SWAT-3 rig of PNC. Regarding an initial pressure spike, analytical and experimental results are compared with each other.

(c) Analytical study on treatment of a boundary between hydrogen and sodium
Shortening the calculation time is required especially when analyzing a large system. Fixed boundary model and boundary tracking model are available in this code. The latter takes the longer calculation time than the former. Capability of adoption of the fixed boundary model is discussed by analyzing a proto-type scale LMFBR.

(d) Preliminary analysis of effects of fluid-induced force on the relief piping
Fluid-induced force is anticipated to be large. To check the effects of the fluid-induced force, the preceding proto-type scale LMFBR is analyzed. Stress of the piping obtained is compared with those due to pressure, thermal transient and earthquake.

2. SOWACS-III CODE

2.1 Outline of Code

The code provides an analytical treatment for the large leak sodium-water reaction.

It covers the phenomena which begin by the leak of water into sodium and end by the pressure relief. It treats failed steam generator, the secondary sodium system and relief system.

The analyses by the code are carried out by the following process;

(a) The generated pressure in the reaction zone and the propagation of pressure and velocity wave are calculated.

(b) Flow-induced force on the relief piping is calculated by the transient of pressure and velocity which was given at the step (a).

(c) This force is used for the analysis of dynamic response of the piping.

SOWACS-III incorporates SWAC-7 code [2] as a subprogram for the analysis of the failed steam generator and embodies the function of analysis of the secondary rupture of tubes.

2.2 Treatment of Secondary Sodium System and Failed Steam Generator

2.2.1 Assumptions and Models

(a) The secondary sodium system consists of the steam generators, valves, intermediate heat exchanger, circulation pump and piping.

(b) The reaction zone is in the failed steam generator and consists of hydrogen.

(c) Water is treated as compressed liquid in the tube. Flow rate can be limited by two phase critical flow.

(d) Leaked water and sodium react instantaneously. Chemical reaction is given as eq. (1).

$$aNa + bH_2O = cNaOH + dNa_2O + eNaH + fH_2 \quad (1)$$

f/b can be specified optionally.

(e) High temperature and pressure hydrogen bubble grows spherically in the initial stage. Afterwards it grows cylindrically pushing the sodium colums.

(f) Hydrogen bubble grows isothermally.

(g) A boundary is formed by contact of sodium with hydrogen. Two boundary models can be treated. One is boundary tracking model in which the boundary travels in the steam generator and piping as hydrogen expands. The other is fixed boundary model in which the boundary is treated not to move from the original place.

(h) Valves are treated as orifices.

(i) Intermediate heat exchangers are treated as pipes.

(j) The circulation pump is treated as a point doing mechanical work of which characteristics are given by the flow-head relation.

(k) The piping and components are treated to be one-dimensional.

2.2.2 Method of Analysis

Leak rate of water is given or calculated by mass and momentum balance.

Fundamental equations for the propagation of pressure wave are as follows;

In spherical co-ordinate

$$\left(\frac{\partial}{\partial t} + V\frac{\partial}{\partial r}\right) H = -\frac{C^2}{g}\left(\frac{\partial V}{\partial r} + 2\frac{V}{r}\right) \tag{2}$$

$$-\frac{1}{g}\left(\frac{\partial}{\partial t} + V\frac{\partial}{\partial r}\right) V = \frac{\partial H}{\partial r} \tag{3}$$

In linear co-ordinate

$$\left(\frac{\partial}{\partial t} + V\frac{\partial}{\partial x}\right) H = -\frac{c^2}{g}\frac{\partial V}{\partial x} \tag{4}$$

$$-\frac{1}{g}\left(\frac{\partial}{\partial t} + V\frac{\partial}{\partial x}\right) V = \frac{\partial H}{\partial x} - \sin\varphi + \left(\frac{f}{d} + \frac{\zeta}{L}\right)\frac{V|V|}{2g} \tag{5}$$

and

$$\frac{\partial P}{\partial \rho} = C^2 \tag{6}$$

The calculation in the failed steam generator is as follows;

Propagation of pressure wave is analyzed with the one-dimensional spherical co-ordinate near the reaction zone and with the linear co-ordinate at the other places [2]. After hydrogen bubble is converted from the sphere to the cylinder, the calculation with the linear co-ordinate is used everywhere.

The explicit method of characteristics in one-dimensional Eulerian co-ordinate is used for the numerical calculation of the equations mentioned above.

2.3 Treatment of Relief System

2.3.1 Assumptions and Methods

(a) The relief system consists of the rupture disks, pressure relief tank and piping.

(b) Flow in the piping is one-dimensional.

(c) Nitrogen in the relief system is a lumped mass and is compressed adiavatically.

(d) A moving boundary is formed by contact of sodium with nitrogen. The boundary travels without mixing of sodium and nitrogen through the boundary.

(e) The rupture disk breaks instantaneously and completely when the pressure at the rupture disk reaches its set pressure.

(f) Two fluid-induced forces are included. One is the force associated with the mass of fluid, the other with the momentum change through elbows.

(g) Coriolis force and centrifugal force caused by the relative motion between piping and sodium are neglected [3].

2.3.2 Method of Analysis

The pressure and velocity of sodium discharged into the relief system are analyzed by the explicit method of characteristics in one-dimensional Eulerian co-ordinate using eqs (4), (5), and (6).

The state of nitrogen is solved by mass and energy balance.

The piping are divided into small straight and curved elements. The fluid-induced force is calculated on every element and is considered to exert at the center of the element.

The method of calculation is described by taking a curved element as an example. Fig.1 shows cross section of the element. A system of co-ordinates and a control surface is determined as shown in Fig. 1. The momentum balance regarding the control surface results in eq. (7).

$$\vec{F} = \begin{pmatrix} F_X \\ F_Y \\ F_Z \end{pmatrix} = \begin{pmatrix} A\rho_1 V_1^2 \cos\frac{\theta_0}{2} \\ 0 \\ A\rho_1 V_1^2 \sin\frac{\theta_0}{2} \end{pmatrix} + \begin{pmatrix} AP_1 \cos\frac{\theta_0}{2} \\ 0 \\ -AP_1 \sin\frac{\theta_0}{2} \end{pmatrix} - \begin{pmatrix} AP_2 \cos\frac{\theta_0}{2} \\ 0 \\ AP_2 \sin\frac{\theta_0}{2} \end{pmatrix} - \begin{pmatrix} A\rho_2 V_2^2 \cos\frac{\theta_0}{2} \\ 0 \\ A\rho_2 V_2^2 \sin\frac{\theta_0}{2} \end{pmatrix} - \frac{\partial}{\partial t}\int \rho\vec{V}dv + \vec{F}_g \qquad (7)$$

Here Fx, Fy and Fz are x-, y- and z- component of the fluid-induced force.

The response of the piping to the fluid-induced force is analyzed by the commercial program NASTRAN [4].

3. Evaluation of Model of Failed Steam Generator

3.1 Experiment

The SWAT-3 [5] is shown in Fig. 2. The SWAT-3 is the test facility to demonstrate the safe design of the steam generator system of the fast breeder reactor Monju against the postulated large leak sodium-water reaction. It consists of a sodium test circuit and an injection water line. The sodium test circuit simulates the secondary sodium system and includes an evaporator, a superheater, an intermediate heat exchanger and piping. The injection water line includes a water tank, rupture disks and piping.

The evaporator which is the reaction vessel simulating the failed steam generator is shown in Fig. 3. The internals of the evaporator consist of a center pipe, helical coiled heat transfer tubes and a shroud.

The water injection hole consists of a nozzle to control the water injection rate and a rupture disk installed at the outside of the nozzle to initiate the leak. The water line runs through the center pipe, and the injection point is located in the annular region of the helical coils with a radially outward injection direction.

Test conditions are shown in Table 1.

3.2 Analysis [6]

The model of analysis is shown in Fig. 4.

(a) The propagation of pressure wave near a water injection point is analyzed with the spherical co-ordinate. The radius of spherical region is equal to the distance between the outer surface of the centerpipe and the inner surface of the shroud shown in Fig. 3.

(b) Effective flow area of the tube bank except the spherical region is calculated by eq (8).

$$A_e = \frac{L}{\int_0^L \frac{dx}{A}} \qquad (8)$$

(c) The centerpipe and downcomer region are combined to be one region.

(d) All regions except the spherical region are analyzed with the linear co-ordinate.

3.3 Comparison of Analysis with Experiment

Analytical result of the initial pressure spike was compared with the experimental result at the pressure detector P1113. The conditions of analysis are shown in Table II. The results are shown in Fig. 5.

(a) The analytical result of the pressure of the first peak was 6.4 ata and the experimental result 6.7 ata.

(b) The analytical result of the rising time of the first peak was 0.6ms and the experimental result 2.8ms.
The difference may be due to the assumption that sodium-water reaction is instanteneous.

(c) The analytical result of the pressure of the first bottom was -5.8 ata and the experimental result +0.3 ata.
The difference may be due to the following reasons.
i) The injection rate of water was approximated by the delta function.
ii) The column separation of sodium is not considered in the analysis, though it would occur when the expansion wave propagated from the cover gas back to the reaction point.

4. Analytical Study on Treatment of Boundary between Hydrogen and Sodium

SOWACS-III provides the boundary tracking model and fixed boundary model as presented in Chapter 2. The difference between two models is studied by the analysis of propagation of pressure wave as follows.

The secondary sodium system and relief system for the analysis are shown in Fig. 6. The secondary sodium system consists of the steam generators, valves, intermediate heat exchanger, circulation pump and piping. The relief system consists of the rupture disks immersed in sodium, piping, pressure relief tank and rupture disk installed on it. These systems were designed for a proto-type LMFBR. Steam generators include an evaporator, superheater and reheater.

The conditions of this analysis are shown in Table III.

Pressure transients at the failure point and the lower tube plate of the evaporator are shown in Fig. 7. The transients of pressure and velocity at the inlet of the upper relief piping of the evaporator are shown in Fig. 8.

(a) For the boundary tracking model, the maximum pressure of the failure point is 31 ata, quasi-static pressure 7.5 ata, the maximum pressure of the evaporator 40 ata and the maximum velocity of the relief piping 31 m/s. While, for the fixed boundary model, they are 31 ata, 8 ata, 40 ata and 31 m/s, respectively.

(b) Pressure transients of two models agree in the first stage. The difference between two models increases with time. It is negligibly small in the evaporator as shown in Fig. 7. While, it is clear at the inlet of the upper relief piping as shown in Fig. 8.

(c) The velocity of the fixed boundary model decreases faster than that of the boundary tracking model.

5. Preliminary Analysis of Effects of Fluid-induce Force on Relief Piping

The fluid-induced force and the response of the piping due to it were calculated regarding the same system shown in Fig. 6 by using the conditions of analysis shown in Table III.

Stresses of the piping were estimated, such as those due to the flow-induced force, pressure, thermal transient and earthquake.

Analytical model of the upper relief piping of the evaporator is shown in Fig. 9.

Fig. 10 shows the fluid-induced force at GRID 6. It shows that the force is exerted since the sodium reaches the elbow. The force of 14.5 ton resulted from the momentum change through the 90° elbow is exerted in the x- and y-direction. In addition, the force in the y-direction includes the weight of sodium that is negligibly small in this case. Fig. 11 shows the displacement in the y-direction at GRID 6. The maximum displacement is 0.95 mm. Fig. 12 shows reaction force on the support in the y-direction at GRID 8. The maximum force is 19 ton.

The maximum stress due to the flow-induced force was calculated based on the result shown above. It appears at GRID 6 and the value was 11.5 Kg/mm^2. Stresses at GRID 6 were calculated based on the following conditions with a view to studying the effects of the fluid-induced force on the piping; i) internal pressure of the piping is 10 Kg/cm^2g. ii) the acceleration by earthquake is 0.439g in the horizontal direction. iii) the piping whose initial temperature is $20^{\circ}C$. is exposed to the thermal transient by the entrance of sodium of $455^{\circ}C$.

The stress at GRID 6 due to the internal pressure was 1.68 Kg/mm^2. the earthquake 0.54 Kg/mm^2 and the thermal transient 16.4 Kg/mm^2.

This comparison indicates that the fluid-induced force plays the important role in the primary stresses.

The integrity of the relief system is assured by the evaluation of these stresses.

6. Conclusion

Analyses were carried out for the large leak sodium-water reaction experiments in SWAT-3 rig of PNC by using the sphere-cylinder model. Velocity and pressure transients in the secondary sodium system and relief system were calculated for the case of simultaneous rupture of four tubes in the evaporator for a proto-type scale LMFBR. Comparison of the boundary tracking model with the fixed boundary model and estimation of effects of the fluid-induced force on the relief piping were performed.

As conclusions, i) the sphere-cylinder model can simulate the initial pressure spike in the system of the SWAT-3 scale, ii) the moving boundary can be approximated by the fixed boundary model that can simplify a computer program and shorten calculation time, iii) the stress due to the flow-induced force would be so high that careful attention is needed for the design of the relief piping, iv) the integrity of the relief system was assured by the evaluation of the stresses due to the large leak sodium-water reaction.

Acknowledgement

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Notation

A :	Flow area	P :	Pressure
Ae:	Effective flow area	r :	Spherical co-ordinate
C :	Sonic velocity	t :	Time
d :	Diameter of pipe	V :	Velocity
F :	Force	x :	Rectangular co-ordinate
Fg:	Force due to gravity	ζ :	Pressure loss factor
f :	Friction coeficient	θ :	Subtended angle
g :	Acceleration of gravity	ρ :	Density
H :	Pressure head	ψ :	Angle of inclination of pipe
L :	Length of Region		

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Table I Test Conditions

		Unit	Run 1
Water pressure		kg/cm²G	153
Water temperature		°C	343
Diameter of injection nozzle		mm	15φ
Duration of injection		sec	7.6
Injection rate		kg/sec	6.7
Total quantity of injection		kg	61.2
Sodium temperature		°C	378
Cover gas pressure		kg/cm²G	0.5
Burst pressure of rupture disk	EV,SH	kg/cm²	3.0(515°C)
	RT		1.5(150°C)
Temp. of relief line		°C	255
Temp. of RT		°C	361
Temp. of drain line		°C	370
Temp. of drain tank		°C	291

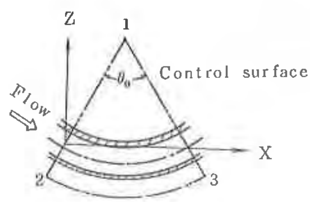

Fig. 1 Curved Element

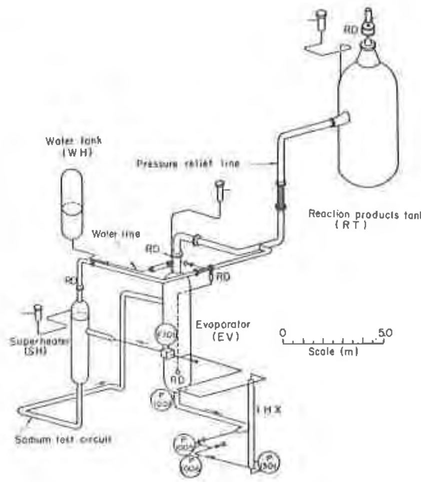

Fig.2 Components, piping layout, and instrumentations of SWAT-3

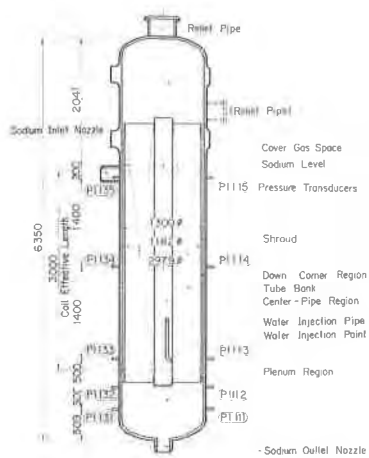

Fig 3 Dimension of Reaction Vessel

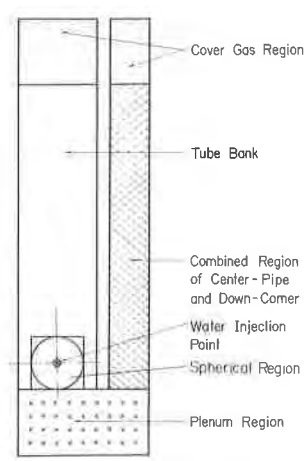

Fig. 4 Combination of Center-Pipe and Down-Comer Region

Table II Conditions of Analysis

Kind of Condition		Description	
Initial Condition	Sodium	V = 0 m/s, T = 387 °C	
	Reaction Region	P0 = 190 ata, R0 = 1cm, T = 1,000 °K	
	Cover Gas	P = 1.5 ata	
Boundary Condition	Free Surface	P = Cover Gas P	
	Bottom	V = 0, (Outlet Nozzle Neglected) m/s	
Physical & Chemical Properties	Sodium Side	Sonic Velocity	1,734 m/s
		Specific Weight	858.8 kg/m^3
		Dynamic Viscosity	3.33×10^{-7} m^2/s
Reaction Model	Chemical Reaction	$2Na + H_2O = Na_2O + H_2$	
	Reacted Water Mass	0.1703 g	
Configuration	Dimension	Fig. 3	
	Radius of Sphere Region	0.21 m	
	Sodium Inlet and Outlet Nozzle	Neglected	

P : Pressure
T : Temperature
V : Sodium Velocity

Table III Conditions of Analytical Study on Treatment of Boundary between Hydrogen and Sodium

Kind of Condition		Description	
Initial Condition	Sodium	V = 0m/s, T = 320°C at Cold Leg T = 450.5°C at Middle Leg T = 510°C at Hot Leg	
	Leak	Size	Instantaneous Guillotine Ruptures of 4 tubes
		Location	Upper tube-to-tube sheet of EV
	Nitrogen gas	P = [illegible] ata	
Boundary Condition	Rupture Disk Rupture Disk (on PRT)	P = 10 ata (Burst Pressure) P = 1.5 ata (Burst Pressure)	
Physical & Chemical Property	Sodium	Sonic Velocity	V = 1531.4 m/s at Cold Leg V = 1461.2 m/s at Middle Leg V = [illegible] m/s at Hot Leg
		Specific Weight	851.4 kg/m^3
		Dynamic Viscosity	3.17×10^{-7} m^2/s
Configuration	Relief Piping	Diameter	20 inch Upper Relief Piping of EV 20 inch Lower Relief Piping of EV 16 inch Upper Relief Piping of SH 16 inch Upper Relief Piping of [illegible]
	Circulation Pump and Valve	Neglected	

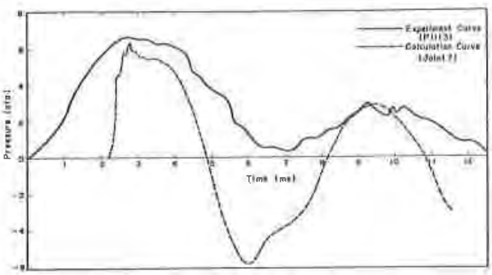

Fig. 5 Comparison of Experiment and Analysis

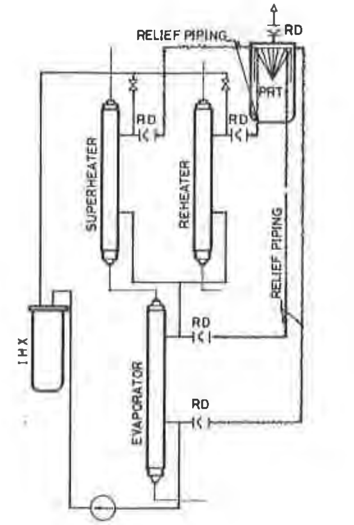

Fig. 6 Secondary System and Relief System for Analysis

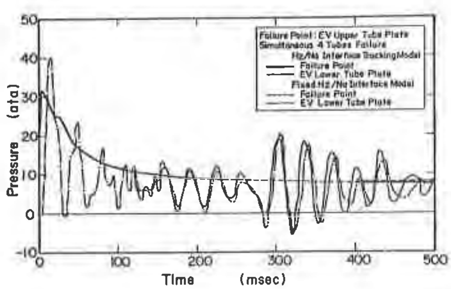

Fig. 7 Effect of Reaction Gas Model on Pressures

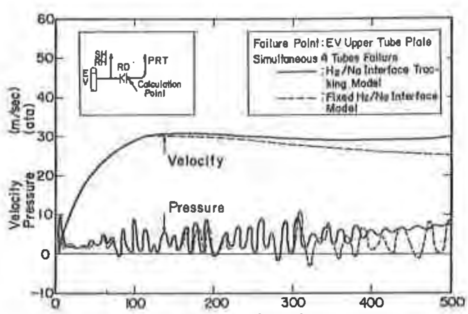

Fig. 8 Pressure and Velocity at Inlet of EV Upper Relief Pipe

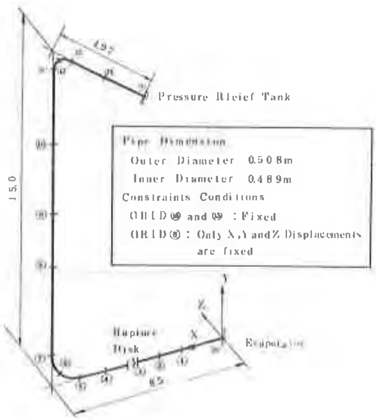

Fig 9. Analytical Model of Upper Relief Piping of Evaporator

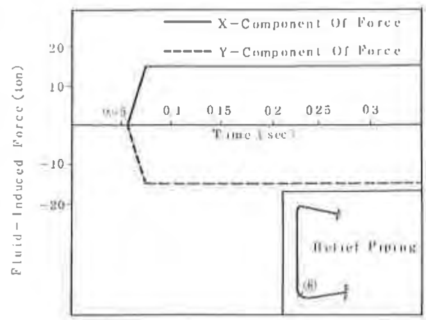

Fig 10. Fluid-induced Force Transient at GRID ⑥

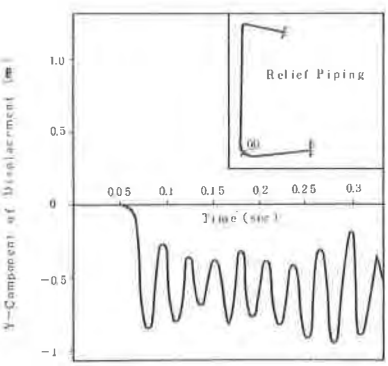

Fig 11 Displacement Transient at GRID ⑧

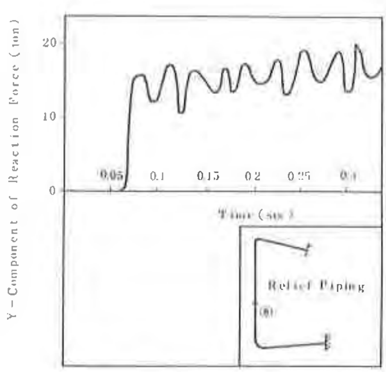

Fig 12 Reaction Force on Support at GRID ⑧