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# Estimation of the Hydraulic Load Experienced in Steam Generator during a Main Steam Line Break

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## ABSTRACT

Internal components of the Steam Generators used in Pressurised Heavy Water Reactors can experience a large thrust force during a postulated Main Steam Line Break. Thus may lead to the mechanical failure of the components. This is an important consideration in evaluating the structural integrity of internal components. RELAP-LOAD, a post processor of the thermal hydraulic safety analysis code RELAP4/MOD6, has been used to predict the short time hydraulic loads. This study estimates the hydraulic load on the Steam Generator internals and the wall.

## 1.0 INTRODUCTION

Steam Generators are used to generate steam from the heat generated in nuclear reactors. The Steam Generators used in the 220 MWe Indian Pressurised Heavy Water Reactors are of vertical U-tube and natural circulation type (Fig.1). The hot primary coolant (heavy water), after extracting the heat from the reactor core enters the U-tubes through the inlet water box and leaves the U-tube through outlet water box after transferring the heat to the secondary coolant (light water). The secondary side of the Steam Generator (SG) is mainly composed of economiser, riser, steam separators, drier, steam drum and downcomer. At full power, the ninety percent of feed water enters into the economiser and the remaining ten percent along with Reheat Condensate Recirculation Flow (RHCRF) enters into the steam drum through a ring header. A flow quality of 20% is achieved with a recirculation ratio (riser flow to steam flow) of 4.3. The separators mounted on the deck plate separate the steam and saturated water, which after mixing with ten percent feed water and RHCRF in the steam drum comes down through the downcomer. The wet steam flows through the set of driers and leaves the steam drum (4.1 MPa) through steam pipe line at 99.99% quality.

A postulated sudden break in the Main Steam Line (MSL) of a PHWR based Nuclear Power Plant (NPP) leads to a blowdown thrust force in the Steam Generators (SGs). The resultant transient pressure field imposes large forces on the steam drum internals like separators, deck plate, driers and feed water distributor. In the riser part of the SG, the tube supports (egg-crate support), downcomer shroud and the tube sheet holding the steam generator tubes will also experience an upward lift due to the drag force during the early stages of blowdown. It is necessary to examine whether these forces may lead to the mechanical failure of the components, which is an important consideration in nuclear safety assessment.

RELAP-LOAD [1], a post processor of the thermal hydraulic computer code RELAP4/MOD6 [2] has been developed to predict this short term hydraulic loads. RELAP-LOAD calculates the thrust force (acting on the wall) which is the algebraic sum of pressure, momentum and acceleration forces in the fluid system, from the thermal hydraulic parameters predicted by RELAP4/MOD6. The hydraulic loads predicted by RELAP-LOAD for the piping system has been well validated with series of experimental [3,4,5] and analytical [6] results described in reference 1.

This paper describes the features of the code RELAP-LOAD, RELAP4/MOD6 specific steam generator model and the methodology to calculate different hydraulic forces experienced by the internals of the SG during such transient.

## 2.0 DEVELOPMENT OF RELAP-LOAD

2.1 Basic equations :

The conservation of mass, momentum and energy must be satisfied among the control volumes and junctions. Eq. (1) shows the momentum equation in the integral form:

$$\frac{\partial}{\partial t}\int_{v} \rho u dV + \int_{s} \rho u (u.n) dS = -\int_{s} P n dS - \int_{s} \tau dS - \int_{v} \rho g dV \qquad (1)$$

The following equation can be obtained by applying eq.(1) to the control volume shown in Fig.2 [7]

$$\frac{\partial}{\partial t}\int_{v} \rho u dV + \int_{s1} \rho_1 u_1 (u_1.n_1) dS_1 + \int_{s2} \rho_2 u_2 (u_2.n_2) dS_2 = -\left[\int_{s1} P_1 n_1 ds_1 + \int_{s2} P_2 n_2 dS_2 + \int_{s3} P_3 n_3 dS_3\right] - \int_{s3} \tau dS_3 - \int_{v} \rho g dV \qquad (2)$$

The only way a fluid can exert a force upon its container is by means of (i) fluid pressure which acts over the wetted surfaces of the container and (ii) friction between the wetted surfaces ($\tau$) of the container and the fluid. Thus we get eq. (3)

$$F = \int_{s3} P_3 n_3 dS_3 + \int_{s3} \tau dS_3 \qquad (3)$$

From eq. (2) and (3) we get the thrust force as,

$$-F = \frac{\partial}{\partial t}\int_{v} \rho u dV + \int_{s1} \rho_1 u_1 (u_1.n_1) dS_1 + \int_{s2} \rho_2 u_2 (u_2.n_2) dS_2 + \int_{s1} P_1 n_1 dS_1 + \int_{s2} P_2 n_2 dS_2 + g\int_{v} \rho dV \qquad (4)$$

Eq. (4) is now applied to the constant area pipe shown in Fig. 3. The density $\rho_i$ and velocity $u_i$ for the ith control volume of length $l_i$ can be linearised by introducing arithmetic average value in the volume. Thus eq. (4) can lead to the following expression for the blowdown thrust force of the $i^{th}$ control volume (pipe).

$$-F = A_i l_i \left(u_i \frac{\partial \rho_i}{\partial t} + \rho_i \frac{\partial u_i}{\partial t}\right) + A_i(\rho_{2i} u_{2i} - \rho_{1i} u_{1i}) + A_i(P_{2i} - P_{1i}) + g\rho A i l i \quad (5)$$

Assemblage of eq. (5) for all the control volume leads to the blowdown thrust force in a single phase flow and homogeneous two phase flow as follows :

$$F= \Sigma_i F = FA + FM + FP + FG \quad (6)$$

where,

Acceleration force : $-FA = \Sigma_i\, l_i\, \delta W_i / \delta t$ (7)

Momentum force : $-FM = \Sigma_i\, A_i\, (\rho_{2i} u^2_{2i} - \rho_{1i} u^2_{1i})$ (8)

Pressure Force : $-FP = \Sigma_i\, A_i\, (P_{2i} - P_{1i})$ (9)

Gravitational Force : $FG = \Sigma_i A_i\, l_i\, \rho g$ (10)

and $\Sigma$ is the summation for all the control volumes

2.2. Coupling with RELAP4/MOD6

RELAP4/MOD6 considers a thermal-hydraulic system as a series of control volumes connected by junctions. Fig. 4 shows a typical example of control volumes I-1, I and I+1 connected by a junctions Z and Z+1 respectively. The RELAP4/MOD6 code solves one-dimensional the mass, momentum and energy equations for volumes assumed to contain homogeneous fluid with the vapor and liquid phases in thermodynamic equilibrium. The code solves the momentum balance at the junctions. The procedure to calculate different forces from the RELAP4/MOD6 predictions is given below.

(i) Acceleration Force (FA): To calculate the acceleration force for a control volume, Eq. (7) has been applied on RELAP4/MOD6 specific model over the control volume I. The acceleration force over the control volume of length L is given by,

Acceleration Force : $-FA_I = L\, [\, (W_I, t+\Delta t) - (W_I, t)\, ] / \Delta t$ (11)

Transient control volume flow rates at t and t+Δt, time step Δt and the control volume length L are used to estimate this force. RELAP4 output of transient control volume flow rates are used as the input to RELAP-LOAD to calculate this force.

(ii) Momentum Force (FM) : The momentum force for a control volume is calculated on applying Eq. (8) over control volume I.

Momentum Force : $-FP_I = [(W^2{}_{z+1}, t)(\gamma_{z+1}, t) - (W^2{}_z, t)(\gamma_z, t)] / A_I$ (12)

Transient values of upstream (Z) and downstream junction (Z+1) mass flow rates and specific volume ($\gamma_z$,t) generated by the RELAP4 run along with control volume flow area are fed into RELAP-LOAD to calculate the momentum force.

(iii) Pressure Force (FP): Applying Eq. (9) on the control volume I, the pressure force is estimated.

Pressure Force : $-FP_I = A_I\,[(P_{I+1}, t) - (P_{I-1}, t)]$ (13)

Transient pressures predicted by RELAP4 simulation for the upstream (I-1) and downstream (I+1) control volumes along with the flow area enables the calculation the pressure force acting on the control volume I.

(iv) Gravitational Force (FG) : Applying Eq. 10 on the control volume I, the gravitational force is estimated.

Gravitational Force : $-FG_I = A_I L\,(\rho_I, t)\,g$ (14)

Transient density ($\rho_I$, t) predicted for the control volumes by RELAP4 along with flow area $A_I$, control volume length L and gravitational constant g, gives the gravitational force.

## 3.0 RELAP4/MOD6 SPECIFIC STEAM GENERATOR MODEL

The above described steam generator has been modelled with 29 control volumes, 31 junctions and 6 heat slabs as shown in Fig. 5. The modelling used for primary and the secondary side are described below.

(i) Primary Side : The primary side is modelled with 11 control volumes simulating inlet water box, outlet water box, tube sheet alongwith the portion of 1834 tubes within it, clubbed 1834 tubes corresponding to the subcooled and two phase flow portion of the riser. Six heat slabs are being used to simulate the heat transfer from primary to the secondary. A time dependent option of RELAP4/MOD6 has been used for the inlet and out let water box to hold the thermal hydraulic condition during the short transient.

(ii) Secondary Side : The secondary side of the SG has been modelled with 18 control volumes. The volume description is given in Fig 5. Three FILL (time dependent flow) options of RELAP4/MOD6 have been used to simulate 90% feed at the economiser, 10% feed in the upper downcomer and Reheat Condensate Recirculation Flow in the upper downcomer. Two LEAK (time dependent flow) options of RELAP4/MOD6 have been used to simulate the normal steam and break flow rates. A Homogeneous Equilibrium Model (HEM) has been used to calculate the critical flow from the break area. The pressure drop in the flow path is achieved with proper loss coefficients. Bubble Rise model, which plays an important role in determining the thermal hydraulic conditions in steady state and transient conditions has been applied to the riser, separators, steam drum and downcomer to simulate the bubble dynamics.

The following assumptions are made for the analysis :

(i) Following MSLB variation in the primary coolant flow is small
(ii) Variation of the feed water flow is negligible during the transient
(iii) Heat transfer between lower downcomer wall and riser fluid is negligible.
(iv) Loss coefficients for steady state are valid for the transient condition.

## 4.0 RESULTS AND DISCUSSION

The main steam line break leads to steam blowdown leading to depressurisation all over the secondary side. The break flow shoots upto 300 kg/s compared to the normal steam flow rate of 92.5 kg/s. As the steam drum depressurisation rate is higher compared to the downcomer, a flow reversal occurs from downcomer to steam drum. A substantial pressure drop occurs across the steam separators due to the high riser flow. The forces across the components are discussed below.

Separators : The drag force coming on the steam separator wall (FSW) is the sum of the forces due to its internal and external flow. The force calculated in the steam drum corresponding to the separator (vol. 20) is distributed on the separator wall and on the steam drum wall according to the surface area ratio. The differential pressure across the separator component gives a large force. The force history for separator is shown in Fig. 6.

Steam Drum Wall : The hydraulic force coming on the steam drum wall (FSDW) is the sum of the forces coming on different parts of the steam drum. The total force is the sum of the forces as given below.

FSDW= Force in the wall in the nozzle area + Force in the steam drum wall beside the drier + Force in the steam drum wall from top of separator to drier bottom + Force in the steam drum wall corresponding to the separator location

Downcomer Shroud : At steady state the downcomer and the riser is having flow in the opposite direction. At 200 ms of the transient the downcomer experience a flow reversal which continues upto 1 s of the transient. The hydraulic force coming on the wall is contributed from the riser as well as the downcomer side. The force calculated in the downcomer control volumes is distributed on the shroud wall surface as well as on corresponding SG wall surface (FSGW) according to the surface area ratio. The transient force coming on the shroud wall (FDS) is depicted in Fig. 6.

Tube Sheet : The force coming to the tube sheet (FTS) is from the drag force coming on the tube wall from inside and outside flow. The frictional force computed in the riser control volumes is distributed between the shroud wall and the tube wall according to the surface area ratio. While computing the SG tube wall force care has been taken to account for the flow and force direction of the internal flow in the SG tube. The force experienced by the tube sheet is depicted in Fig. 7.

For computing the total force (FT) acting on the SG wall, it is assumed that the force experienced by the separator, downcomer shroud and tube sheet will get transmitted to the SG wall as they are connected to the same. Ft is the sum of the following forces,

FT= FSW+FSDW+FDS+FSGW+FTS

The computed total force (FT) transient is depicted in Fig. 7.

## 5.0 CONCLUSION

A methodology has been evolved for estimating the total transient hydraulic forces acting on the SG wall as well as the internal components. This approach can be used for designing the internal components and the support system of the SG.

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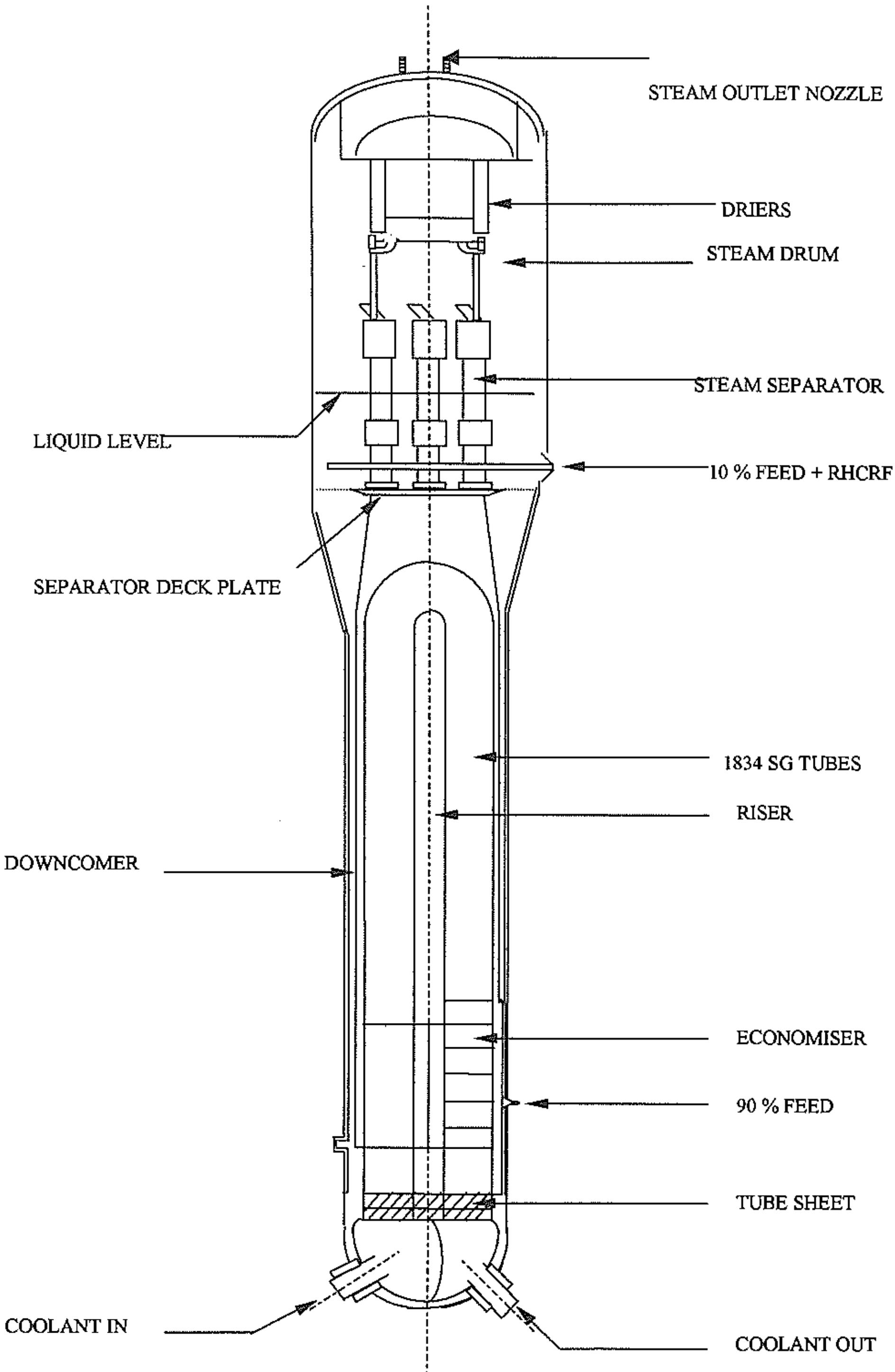


**Fig. 1: Schematic of Steam Generator Used for 220 MWe PHWR**

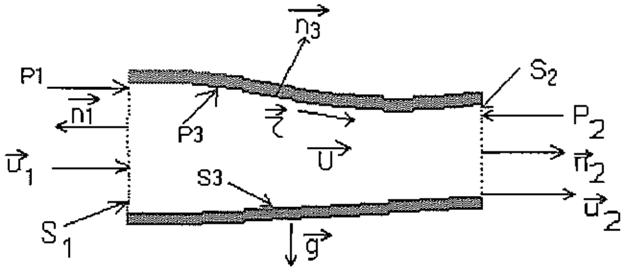


Fig. 2 : Control volume for thrust force calculation

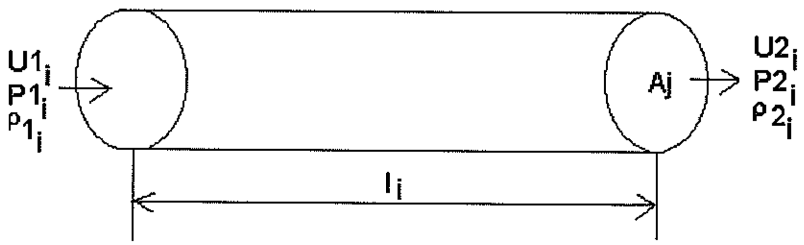


Fig. 3 : Control volume of constant area

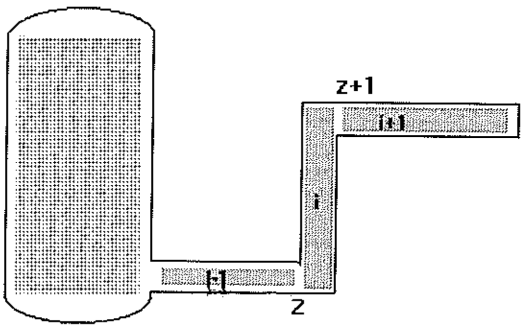


Fig. 4 : Typical example of control volumes and junction

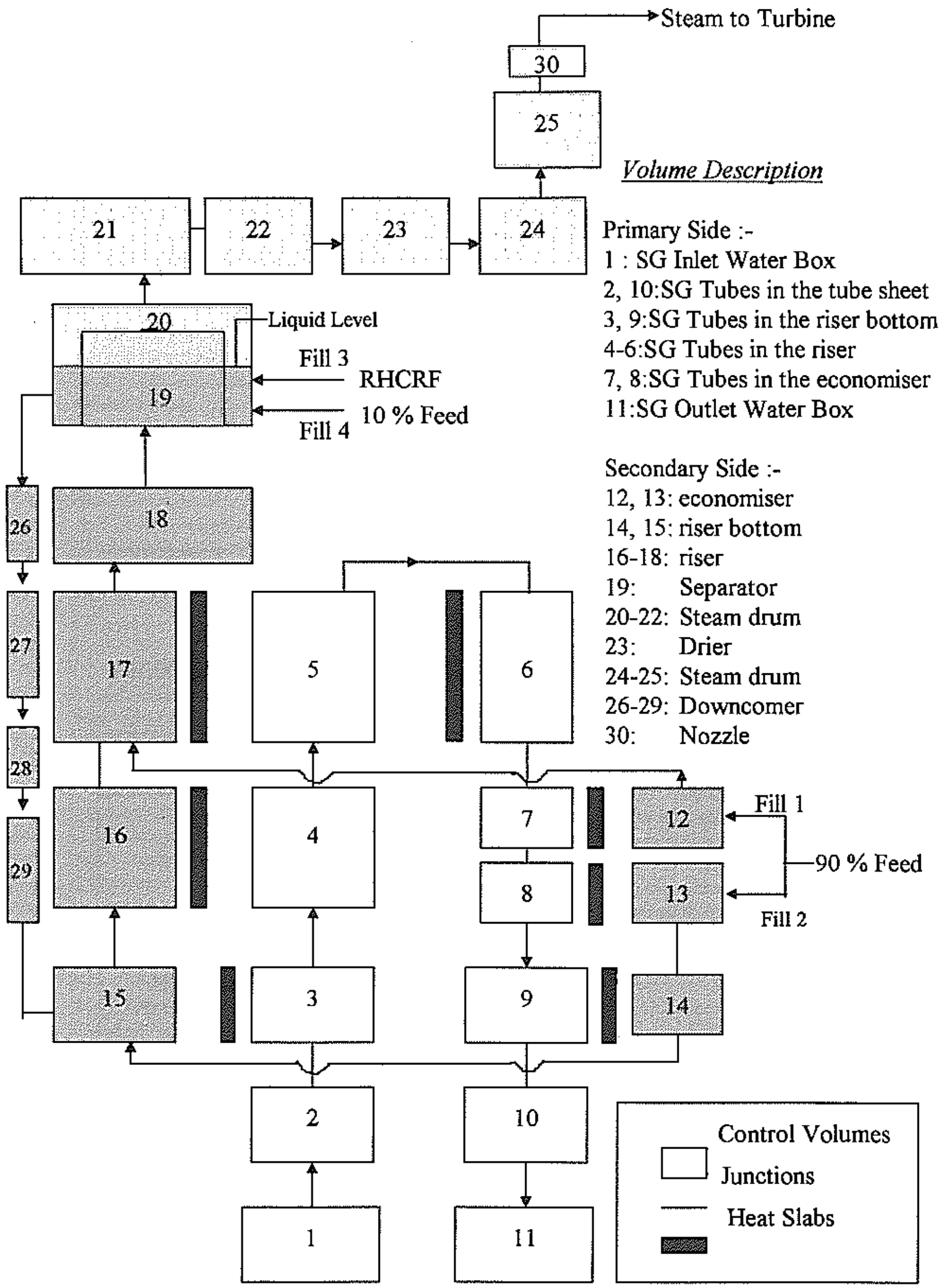


**Fig. 5 Nodalisation Scheme of Steam Generator**

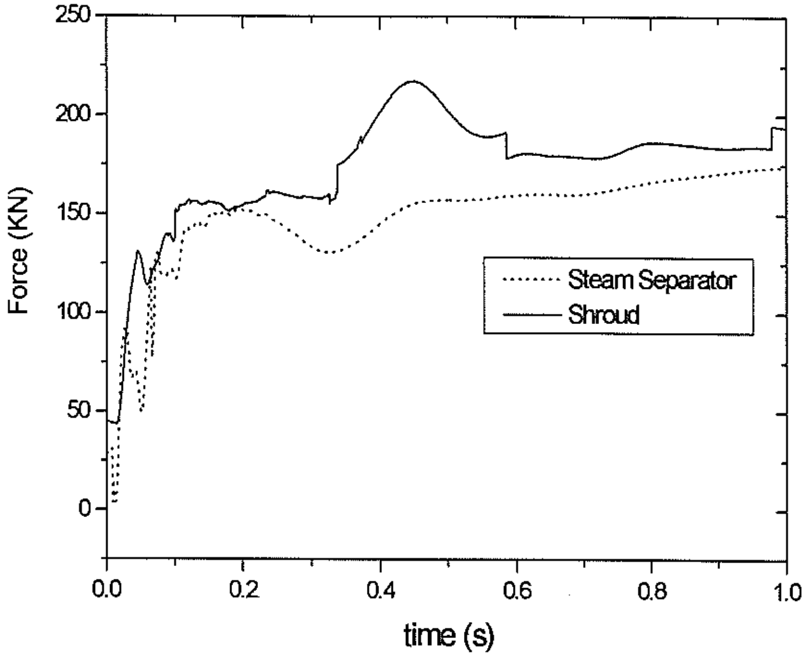


Fig. 6 : Drag Force Transients for SG Components

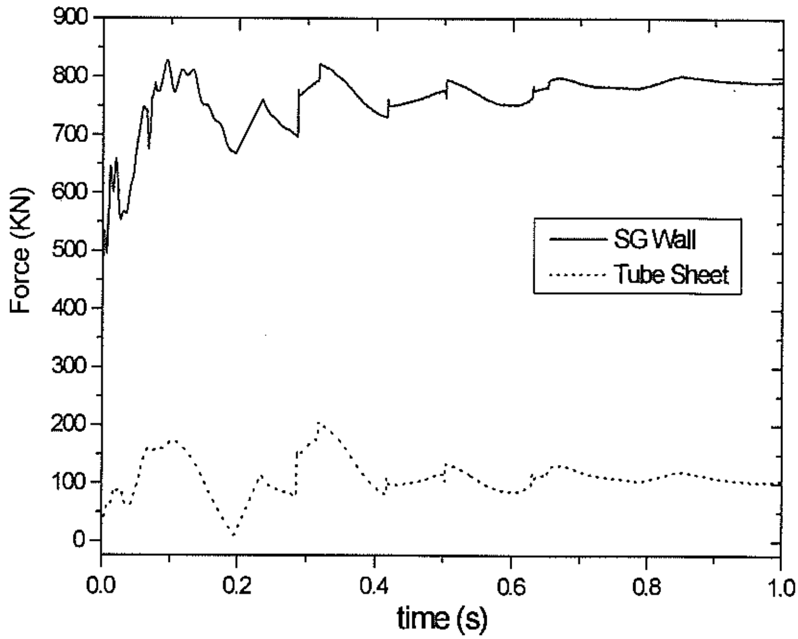


Fig. 7 : Drag Force Transient for Steam Generator