DYNAMIC ANALYSIS OF NUCLEAR EQUIPMENT SUPPORTS

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ABSTRACT

Special provisions are made in the design of major equipment supports to accommodate postulated loss-of-coolant or steam line break accidents. Using a large order finite element program, a detailed analysis of an 800 Mwe, 3 loop nuclear steam supply system was performed. The objective was to determine the adequacy of the steam generator and reactor coolant pump supports under dynamic loading conditions in a ruptured loop or induced in one of the two adjacent loops. Results indicate the inadequacy of static analyses when dynamic transients exist and the necessity of a complete analysis to optimize support design.

1. INTRODUCTION

The support design for major equipment items such as the reactor pressure vessel, steam generators, reactor coolant pumps, and pressurizer must accommodate in addition to the normal operating loads, the postulated loadings arising simultaneously from a loss-of-coolant accident and the design basis earthquake. Current support design practice includes provisions to prevent unacceptable extension of the accident consequences.

The solution of the loss-of-coolant accident problem in pressurized water reactors involves the transient analysis of a complex thermal and hydraulic system. The results of the blowdown analysis are used to generate forces around the reactor coolant loop which are defined as time-history forcing functions, and the points of application applied at changes in flow direction or changes in boundary size. This forcing function data for a time span of one second includes the specific jet thrust at the break location, the internal hydraulic forces resulting from the propagation of the shock waves, and flow inertias within the broken and unbroken loops. Blowdown analysis data were supplied by the vendor of the nuclear steam supply system.

A mathematical model of the equipment, piping, and associated equipment supports was constructed for one loop of a three-loop, 800 Mwe pressurized water reactor plant. Using the blowdown forcing functions dynamic structural responses were investigated for both the longitudinal splits and double-ended circumferential pipe ruptures. The primary objectives of this paper are to describe briefly the steam generator and reactor coolant pump supports and to present some of the dynamic analysis results.

2. DESCRIPTION OF SUPPORTS

Figures 1 and 2 show the general arrangement in elevation and plan view of an 800 Mwe nuclear power plant. The steam generator upper and lower supports and the pump support arrangement for one loop of such a plant is given in Figure 3.

In the steam generator support system, the upper support ring transmits horizontal forces from the steam generator through four hydraulic snubbing cylinder assemblies to the reinforced concrete charging floor. Each of these cylinders allows free thermal motion but reacts to a suddenly applied force resulting from an earthquake or a loss-of-coolant accident. The charging floor transmits these forces to the reactor shield walls and to the crane and cubicle walls where, the forces are transmitted downward to the base mat by shear.

The four support feet or pads on the steam generator bottom head are attached to the lower steam generator support frame. These connections allow radial thermal expansion of the four support pads but transmit all the tangential and vertical forces. The lower support frame is anchored to the cubical floor at six points which allow free motion in a direction parallel to the line running from the reactor pressure vessel to the steam generator inlet nozzle (hot leg). The attachments at the four corners transmit only the vertical loads, while the remaining two transmit only horizontal loads in a direction perpendicular to the hot leg. This combination of snubbing cylinders and the sliding support permits thermal expansion of the hot leg.

The connection between the reactor coolant pump and support frame permits radial thermal expansion of the pump feet. This frame is supported vertically by three pin-ended columns which allow free movement in the horizontal plane to accommodate thermal expansion of the reactor coolant piping. Lateral support is provided by hydraulic snubbing cylinders between the pump support and the steam generator lower support frame and between the pump support frame and the reactor shield wall.

3. MATHEMATICAL MODEL

The extent and nature of the mathematical model used to represent the real structural system in a dynamic analysis significantly affect the validity of the generated results. Excluding cost factors, the decisions of what to include and what to neglect can be based only on sound engineering judgment and experience.

Based on a preliminary evaluation, it was decided to model only one of the three loops in detail. The hot and cold legs of the model illustrated in Figure 4 were terminated at the reactor vessel nozzles which were considered fixed. Calculations of the relative stiffnesses of the reactor vessel supports, reactor vessel nozzles and primary shield wall indicated that these stiffnesses were sufficiently high in comparison to the stiffnesses of the model components to justify this assumption.

The complex steam generator support frame was modeled, and using the "ICES STRUDL" program, the equivalent overall stiffnesses of this structure were calculated and inserted into the mathematical model for dynamic analysis.

The mathematical model also includes the cold leg, pump suction line, hot leg, and main steam line up to the first anchor point. The steam generator and reactor coolant pump masses were concentrated at several mass points. Mass distribution of the piping and support components were approximated by lumped masses at frequent intervals. Axial, shear, and bending stiffnesses of the piping were included in the mathematical model while beams with appropriate properties were used to represent the steam generator and pump support components.

Figure 4 represents an unbroken loop mathematical model which was modified to reflect the geometrical discontinuities associated with the particular break investigated for the ruptured loop analysis. The mathematical model consists of approximately 77 nodes, 80 members, 362 static degrees of freedom and 105 dynamic degrees of freedom.

4. DYNAMIC ANALYSIS - PIPE RUPTURE

A total of eleven breaks (4 guillotines, 7 longitudinal splits) were considered in the dynamic analysis. The locations of the breaks and the points of force application are indicated in Figure 5. Pipe break loads were based on the full cross-sectional area of the pipe for both the longitudinal splits and double-ended pipe ruptures. Forcing function data forwarded on tape by the nuclear steam system supplier covered ruptures in the reactor coolant lines only. For main steam line ruptures, the forcing function was assumed to have a rise time of 0.015 second to the maximum value equal to the cross-sectional area times 1.25 the design pressure. The factor of 1.25 was included to account for the flow coefficient.

As indicated previously, the longitudinal split was assumed to have a break area equivalent to the cross-sectional area of the pipe. However, the orientation of the force around the circumference of the pipe, as well as the location of the force along the pipe, was arbitrary although the critical locations for this type of break were determined on a trial and error basis. For a particular run of pipe, several locations or orientations were required to ensure that all support components were subjected to the maximum postulated load. This accounts for the greater number of longitudinal splits investigated, i.e., 7 splits versus 4 guillotines.

The load imposed on the equipment/support system was assumed to be limited by the load-carrying capacity of the pipe. The calculations for the moment capability of the pipe included the shear effects of the transverse load. For longitudinal splits, the force perpendicular to the pipe was located such that the plastic bending moment capabilities of the pipe would not be exceeded based upon static considerations. Since it is theoretically possible to yield the pipe under a pure shear load, the minimum break length considered for developing the full cross-sectional area of the pipe was conservatively assumed to be one pipe diameter. Furthermore, the pipe properties of the break area were conservatively assumed to be equivalent to the properties of the unbroken pipes. These two assumptions tended to bound the maximum shear load which could be induced into the equipment/support system.

For each set of pipe properties, moment-shear interaction curves were generated based on limit theorems to ensure that the maximum possible load was acting on the equipment/support system. The output data of the dynamic analysis were examined to verify that a plastic hinge was neglected in assessing the maximum component support loads.

The "STARDYNE" computer program was used to perform the dynamic analysis. "STARDYNE" consists of a series of compatible digital computer programs designed to analyze linear elastic structural models either statically or dynamically. The program is based on the "Stiffness Method" and its range of applicability is limited to small displacement theory.

The size of the mathematical model was such that the problem fell within the permissible range of dynamic degrees of freedom for use of the Householder-QR option to calculate the natural frequencies, characteristic mode shapes, and modal participation factors. The modal data output was combined with the forcing function data to determine the transient structural response. Modal damping of one percent critical was assumed.

The response of the structural system was examined for the first second after the postulated occurrence of the pipe rupture. Over this interval 40 to 60 intermediate time points were required to define adequately the structural response. The selection of these points was based upon forcing function shapes and preliminary response analyses.

The dynamic analysis output consisted of displacement, velocity, and acceleration time-histories at all nodes of the mathematical model. The results thus generated were used to calculate equivalent static loads. The maximum deflections and rotations obtained as output at the lower steam generator support were inserted into a detailed "ICES-STRUDL" program model to calculate the individual component member stresses.

5. RESULTS

The stiffness characteristics of the total model reflect the location and the nature of the break. For longitudinal splits, it was conservatively assumed that the pipe properties in the vicinity of the break were the same as for the unbroken pipe to ensure that the maximum loads were transmitted to the equipment/support system. For the guillotine breaks, the pipe at the break was considered to be completely severed. Since the first three natural frequencies (6.54 to 11.07 Hz) did not vary significantly for the various breaks considered, the major contribution to the stiffness of the model comes from the support system whereas the influence of the piping with respect to the natural frequencies is secondary. The minor variations in the natural frequencies with break location reduce the number of mathematical models which must be evaluated seismically causing a significant reduction in the computations performed.

Although it is possible to extract all of the natural frequencies of the system, a limited number of frequencies is generally selected. An examination of the significance of the number of modes used in the time-history analysis indicated that the dynamic response can be adequately approximated with the first 30 natural frequencies.

The blowdown forces caused by a rupture of a reactor coolant pipe include the specific jet thrust at the break location and the internal hydraulic forces resulting from the acceleration of the fluid within the broken and unbroken loops. A static design analysis generally considers only a static force applied at the break and neglects the mechanical response of the total system. In order to evaluate the significance of the internal hydraulic forces for a hot leg guillotine break, dynamic responses were determined for two loading cases. For the first case, the system loading consisted only of the jet thrust time-history at the break (Node 58, Figure 5). The second loading case considered in addition to the jet thrust at the break, the internal hydraulic forces represented by the numbered nodes shown in Figure 5.

The vertical displacement of the steam generator bottom head (Node 19, Figure 4) for the above two loading cases is presented in Figure 6. It is evident that the steam generator internal hydraulic forces produce a vertical unbalance which is considerably more significant than the jet force loading. Figure 7, giving the vertical displacement at the top of the pump (Node 14, Figure 4), indicates maximum displacements for both loading cases approximately 0.055 - 0.060 seconds after the break. The maximum displacement, when all of the blowdown forces are applied, is almost three times the displacement associated with the first loading case. Because of the shock waves that result from the transient, the mechanical response of the system may be inadequately described by either a static or dynamic analysis which considers only the action of a single force at the break.

During a loss-of-coolant accident, the reactor coolant system undergoes a severe pressure transient. The internal hydraulic forces will develop component reactions in the unbroken loops. The majority of the support reactions are considerably smaller for the unbroken loops than the corresponding support reactions in the ruptured loop. Figure 8 indicates that the steam generator bottom head displacement in the X-1 direction is several orders of magnitude greater for the broken loop than the corresponding unbroken loop displacement. In Figure 9, the vertical displacement of the steam generator bottom head for the unbroken loop is significant although it lags somewhat the broken loop response.

Preliminary design loads were established based upon the shape of the forcing functions and the expected dynamic response of the complete equipment/support system. Equivalent static loads ranging from 1.11 to 2.50 operating pressure times cross-sectional area were applied at the break locations. Hydraulic snubber assembly loads obtained from static and dynamic analyses are indicated in Table I. It is readily evident that the magnitude of the loads used for preliminary design and sizing of the members differ by as much as 50 percent from the dynamic analysis results. Although the static versus dynamic results in several of the members were not in close agreement and these members were subsequently redesigned, the majority of the support members were adequate and no further redesign was necessary.

6. CONCLUSIONS

Results of the dynamic analyses indicate the complex nature of the problem and confirm the expectations that component support load calculations based upon static analysis considerations may be inadequate. The internal hydraulic forces are significant and a design based on a jet thrust loading, only at the break, may underestimate some of the member loads by 50 percent. Also the contribution to component member loads from cross-coupling effects is not predicted by static analysis. For example, a guillotine break of the pump suction line at the lower portion of the pipe induced a large vertical excitation of the pump, although the force at the break was acting in a horizontal plane. The pump excitation was reduced by altering the stiffness properties of the pump support columns.

It is difficult to suggest a constant amplification factor to be used on either the operating or saturation pressures of the line to arrive at suitable design loads. Some relief was obtained in the magnitudes of the calculated member loads based on dynamic analysis results because the maximum moments and forces loading the support components were generally out of phase. The effect of phasing is, of course, a function of the support system stiffness characteristics and the nature and location of the breaks considered.

In retrospect, initial design loads for pipe break for the support system indicated in Figure 3 could have been approximated by multiplying the operating pressure by the cross-sectional area of the pipe and allowing a factor of 2.0 to account for the dynamic effects. Design loads of this magnitude will be conservative if the load sharing capabilities of the unbroken legs of the pipe are neglected in the initial support design. Since some of the support members will obviously be substantially overdesigned if the above static loading criterion is used, dynamic analyses must be performed to optimize the support design.

TABLE I

A COMPARISON OF STATIC AND DYNAMIC RESULTS

Break	Hydraulic Snubber	Preliminary Static Design		Dynamic Analysis
		Applied Force at Break X (Pressure x Break Area)	Member Load x (Pressure x Area)	Member Load x (Pressure x Area)
Hot Leg	1-13	1.450	.819	1.042
Guillotine	16-25	1.450	.674	.703
Cold Leg	42-56	1.106	.413	.353
Guillotine	43-44	1.106	.402	.340
Steam Line Split in Direction X-1	3-6	2.500	2.745	4.010
Steam Line Split in Direction X-2	5-6	2.500	1.849	1.621

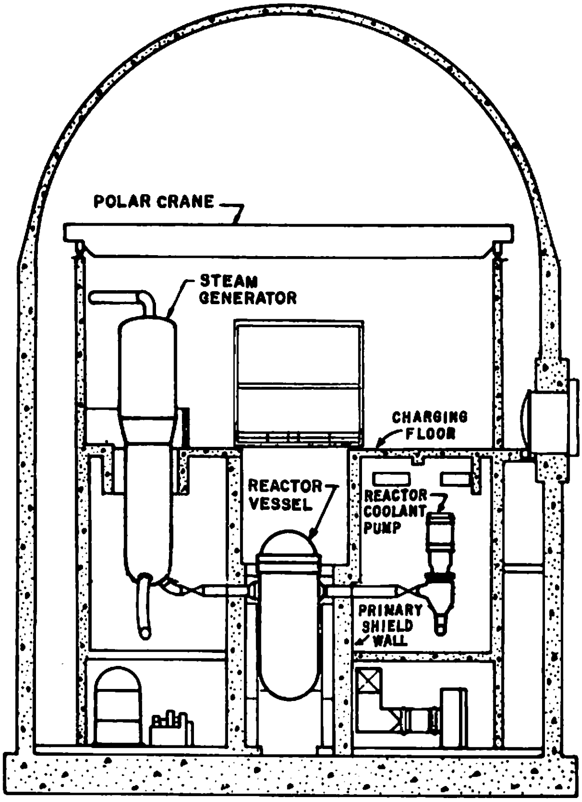

Figure 1 - General Arrangement - Elevation

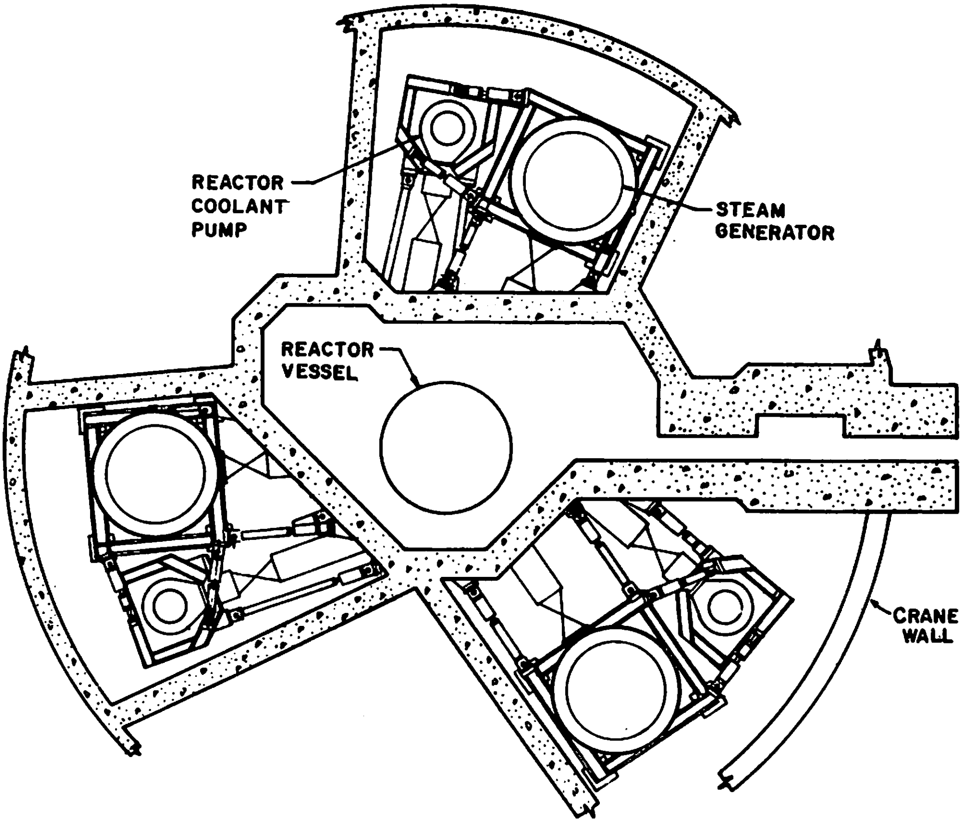

Figure 2 - General Arrangement - Plan View

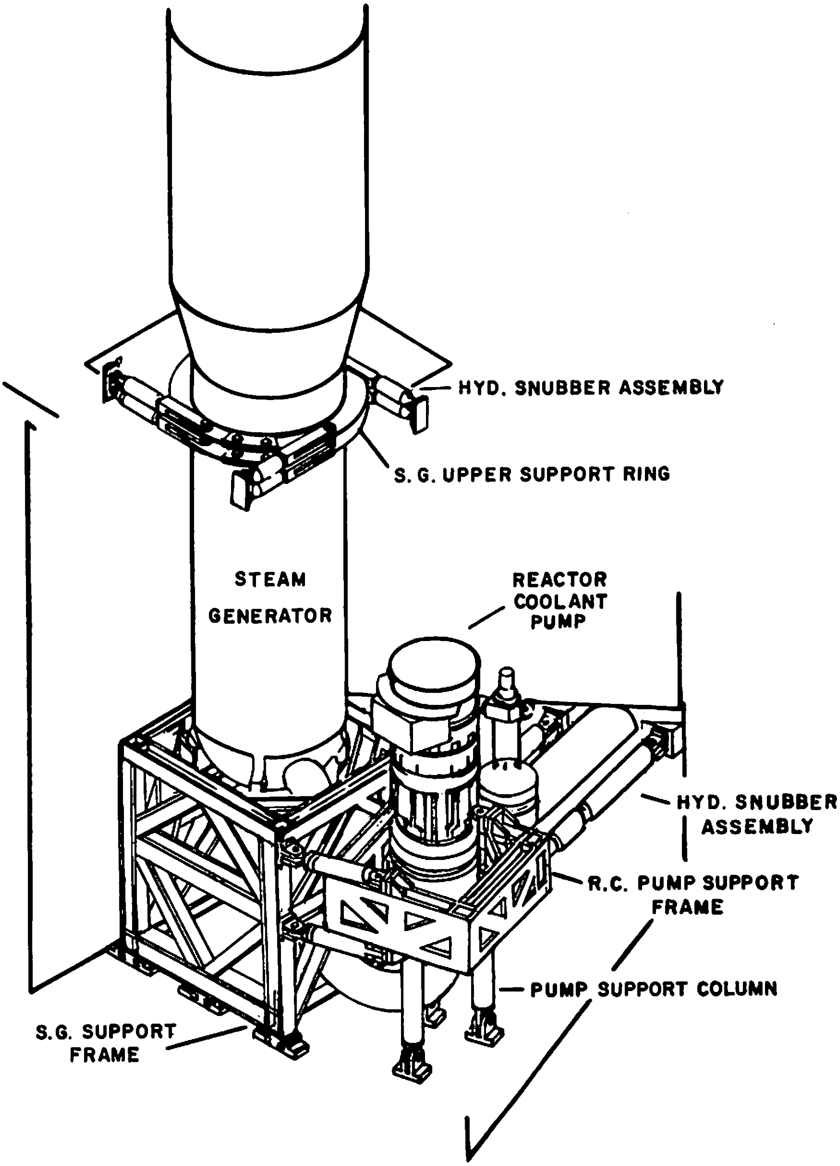

Figure 3 - Steam Generator and Pump Support System

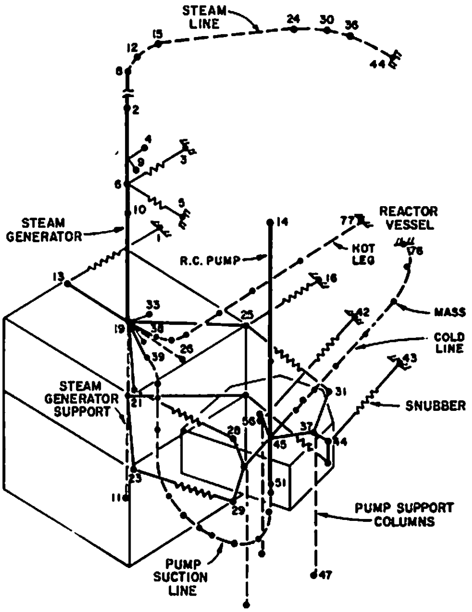

Figure 4 - Mathematical Model

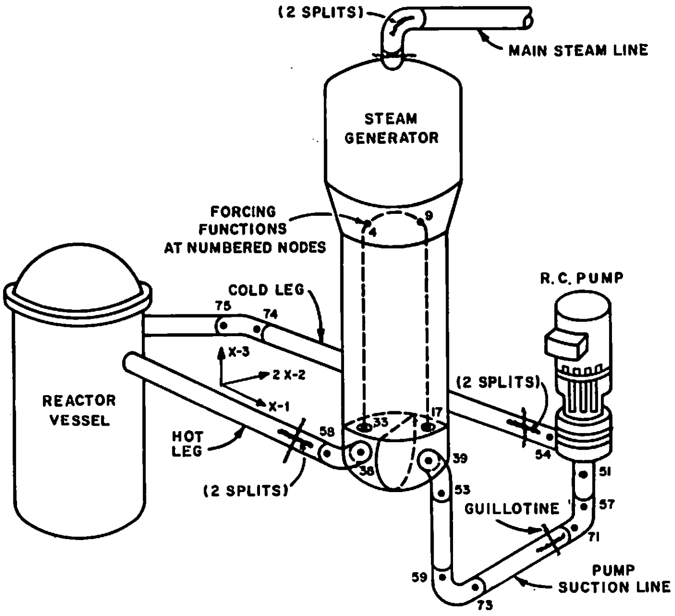

Figure 5 - Break and Force Application Locations

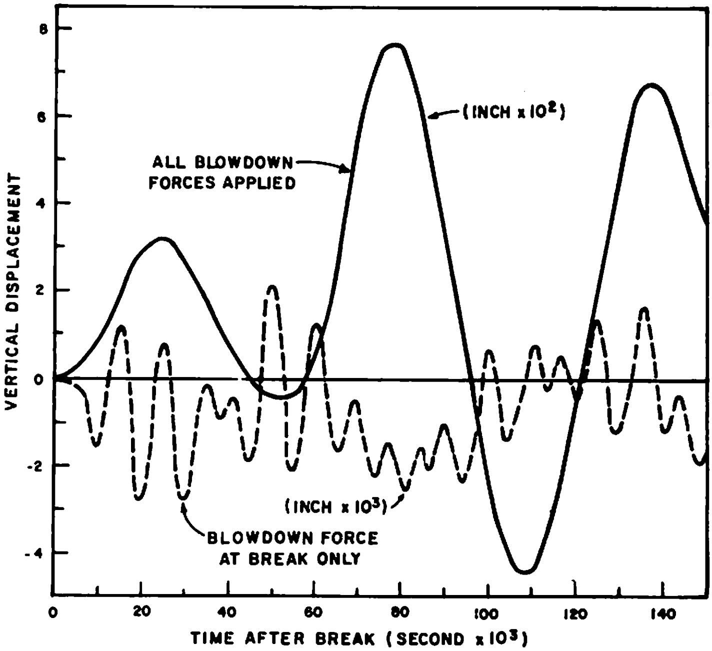

Figure 6 - Effect of Internal Hydraulic Forces on Steam Generator Bottom Head - Hot Leg Guillotine

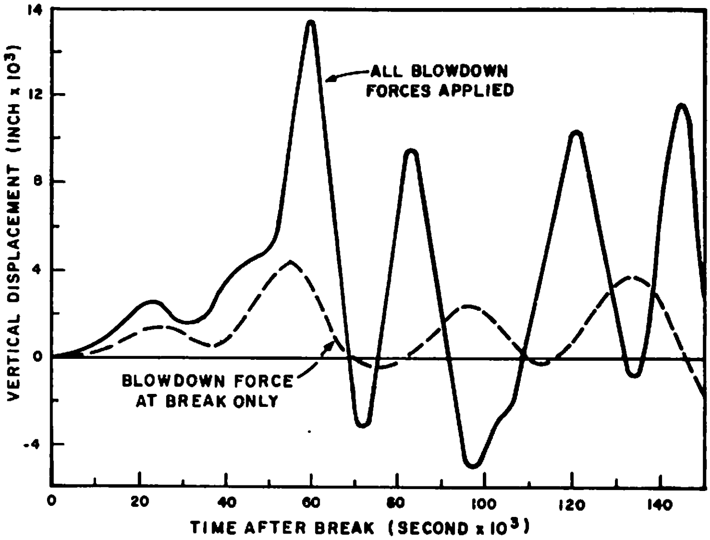

Figure 7 - Effect of Internal Hydraulic Forces on Pump Top - Hot Leg Guillotine

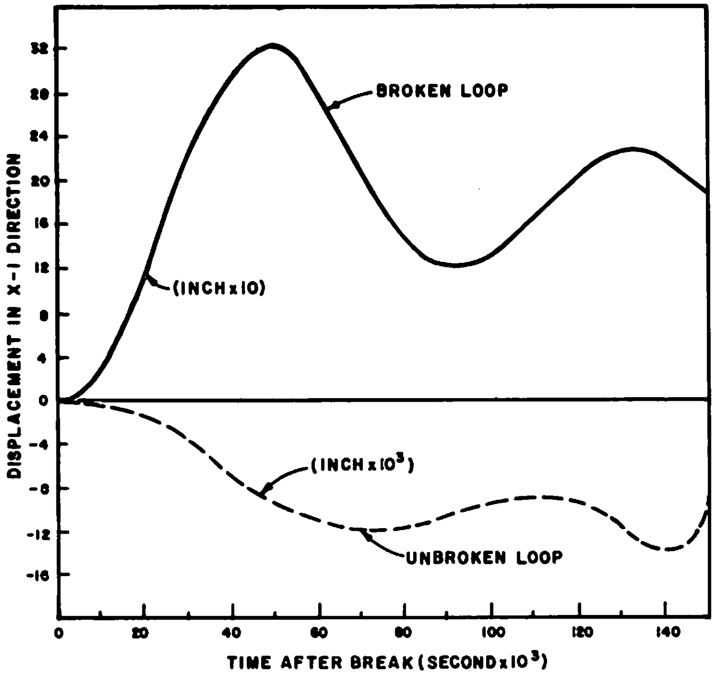

Figure 8 - Steam Generator Botton Head Displacement in X-1 Directicn - Broken and Unbroken Loop

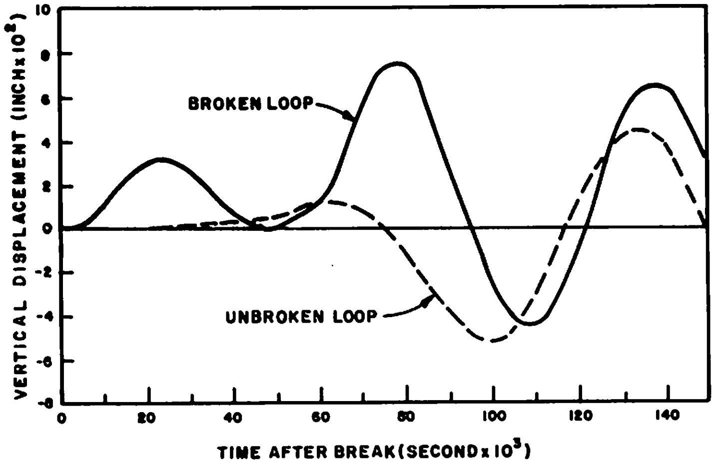

Figure 9 - Steam Generator Bottom Head Vertical Displacement - Broken and Unbroken Loop

DISCUSSION

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J. A. DEARIEN, U. S. A.

In your analysis, what initial conditions did you assume for the stress state of the piping system ?

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Unstressed piping system. However, the way we apply the forcing functions and test on smaller system make our results compare with analysis with prestressed piping system as boundary conditions.