



Dynamic Analysis and Seismic Upgrading of the Reactor Cooling Systems of the VVER-440/213 PAKS 1-4

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ABSTRACT

The dynamic behavior of the reactor coolant system (RCS) was evaluated and studied in detail on the basis of the results of a dynamic calculation (eigenmodes, relative displacements, acceleration response spectra). The findings of the evaluation of the results obtained for the as-built status provided the first upgrading option and indication for arrangement of dampers introduced for stabilizing the reactor coolant system.

In order to evaluate the efficiency of the adopted dampers and their location, comparisons were performed on the basis of the results of different upgrading concepts considering the available gap (horizontal and vertical) of the dampers as well as the thermal expansion effects of the RCS loops. By evaluating the results obtained for a number of subsequent upgrading options, it was possible to define the final retrofit concept for the reactor coolant system.

The final retrofit option represents the basis for the upgrading measures as well as the calculation of the final response spectra. The results will be demonstrated and discussed.

1 INTRODUCTION

In order to investigate the reactor coolant system in detail and select an optimal upgrading concept, a number of investigations were performed for a range of stabilization options. The starting point of this investigation were the data of the real dynamic behavior of the reactor coolant system (RCS) obtained for the as-built status by means of a complex mathematical model (composed of the RCS and the supporting concrete-block structure).

This led to the conclusion that, due to the relatively large displacements (particularly those of the steam generators, see Table 3), additional stabilizing elements (viscous dampers) would have to be installed in order to reduce the dynamic response of the RCS loops and components. This is mainly attributable to the very flexible structure of the RCS which is designed to accommodate the thermal expansion and contraction during operation. The dynamic behavior of the reactor coolant systems has therefore been calculated for a number of upgrading options considering a different arrangement of stabilizing elements (dampers) supporting the steam generators and the main cooling pumps of every loop. The results were evaluated and the most effective upgrading concept was finally selected.

The selection of the most effective upgrading concept was based mainly on the detailed evaluation of the following dynamic response results:

- Maximum displacements and accelerations
- Values of total forces and stresses
- Fundamental frequencies (transfer functions).

The investigations performed with regard to the definition of the most effective upgrading option were performed for the representative soil condition G_{max} .

2 DESCRIPTION AND IDEALIZATION OF THE STRUCTURES

The design details of the structures of the reactor coolant system are described in several engineering reports [1] and [2]. The general arrangement of the RCS is shown in Figures 1 and 2, and the layout of the loops in Figure 3.

The supporting concepts of the main components, the reactor pressure vessel (RPV), the main coolant pumps (MCPs) as well as hot and cold legs are shown in Figures 3 and 4.

The RCS loops as well as the associated components were idealized by means of equivalent piping, beams and spring elements. Figure 5 shows the three-dimensional mathematical model of one loop, while Figure 6 illustrates the global model of all six loops.

The reactor building concrete block (RBCB) supporting the primary system was idealized by means of a three-dimensional mathematical model composed of quadrilateral and triangular plate elements (Figure 7).

In order to consider the coupling effects between the RCS and the supporting structure as well as to introduce correctly the excitation on the rather large number of supporting and connection points of the RCS, the two models (RCS + RBCB) were coupled as specified in [3] to form a single complex mathematical model.

The real interaction between the reactor building concrete block and the soil on the site is represented by frequency-dependent impedance functions (obtained as part of the analysis of the main building complex) distributed over all nodal points of the foundation of the RBCB. It is thus assumed that the capability of the soil foundation to absorb translational, rocking and torsional motion as well as its radiation and hysteretic damping is considered realistically.

Three artificial acceleration time histories derived from the site-specific free-field spectra were applied simultaneously in order to simulate an earthquake. The horizontal time histories defined in [1] were scaled to 0.25 g and the vertical time histories to 0.2 g. In order to take into account the embedment level of the building, the time histories were deconvoluted to the foundation level. Figure 8 shows the spectra at embedment level.

3 CALCULATION FOR AS-BUILT AND UPGRADED CONDITIONS

Frequency-domain analyses using the SASSI computer code [5] were performed for every option of the reactor coolant system in order to derive the dynamic response results for the as-built conditions during an earthquake excitation of the reactor concrete block.

By analyzing the eigenfrequencies (Table 1) and mode shapes (Figures 9 to 11) obtained for the as-built condition (Option 0) it was possible to determine the region and direction in which the RCS damping forces should be effectively implemented. After preselecting the stabilization elements and the locations of the dampers, calculations were performed in order to derive the relative displacements (Tables 2 and 3) and forces/stresses (Tables 4 and 5) acting in characteristic regions. The tables for forces and displacements show the maximum values of all six loops.

The following were identified as the most representative regions:

- The edges of the steam generators (displacements and stresses)
- Cold loop near MCP (displacements and stresses)
- Hot loops near valves (displacements and stresses)
- Hot and cold loop close to the RPV nozzle (forces, stresses)

For every upgrading option, the status of stresses in the loops due to earthquake loading as well as stresses caused by normal operation were combined and evaluated (Tables 4 and 5).

4 UPGRADING OPTIONS

Considering the pronounced thermal expansion of the RCS loops, the only reasonable approach with regard to stabilizing the components and loops would appear to be the implementation of viscous dampers.

On the basis of the required capacity of viscous dampers and considering the available space for implementing the damping devices, Gerb-type /6/ viscous dampers (VES 100) were selected (Tables 6).

The VES 100 dampers act in the vertical and horizontal (radial) directions. The behavior of dampers is defined by the damping resistance as a function of frequency. The characteristics of the dampers for the horizontal direction are shown in Figures 12. For the selected VES 100 dampers, the resistance curve for the vertical direction are also shown in this graph.

On the basis of the eigenmodes obtained for the as-built conditions as well as the relative displacements in the above characteristic regions of the (Option 0) as-built conditions (Option 0), the following upgrading versions were determined and analyzed independently in subsequent steps:

- a) Option 1 (4+0) (see Figure 13)
 - Stabilization of the steam generators by means of 4 VES 100 dampers located accordingly between the steam generator (SG) traverses and the repository supports.
- b) Option 2 (4+1) (see Figure 14)
 - Stabilization of the steam generators by means of 4 VES 100 dampers.
 - Stabilization of the MCP by one VES 100 on the loop downstream of the pump
- c) Option 3 (6+1) (see Figure 15)
 - Stabilization of the steam generator by means of 6 VES 100 dampers
 - Stabilization of the MCP as above
- d) Option 4 (8+1) (see Figure 16)
 - Stabilization of the steam generators by means of 8 dampers
 - Stabilization of the MCP as above

5 EVALUATION OF RESULTS

By comparing the relative displacements derived for different options (numbers of dampers) it was possible to clarify the possibilities reducing the relative displacements of the steam generators. It could be observed that by means of only 4 dampers (two dampers on every support) installed between the SG and the supports, the relative displacements could be reduced by a factor of more than three. The relative displacements were calculated for different upgrading alternatives as well for the thermal expansion.

The forces and stresses due to seismic and normal operational loads were evaluated accordingly for characteristic regions of the reactor coolant system.

The stresses in the characteristic regions of the pipe cross-section were derived from the axial forces and moments, and for the axial forces combined with bending moments.

In order to select the most appropriate alternative, the seismically induced forces in the characteristic regions of the reactor coolant system (the connection to the loops to the RPV the SG and the MCP) are summarized (maximum values over all 6 loops) in Table 4. The values given for the stresses are only intended for selecting the upgrading concept and have been calculated without code considerations.

In order to demonstrate the total status of stresses due to seismic and normal operational loads (deadweight, pressure, temperature) the stresses for the above characteristic regions are summarized in Table 5.

Figure 17 shows the comparison of transfer functions from the "as-built" condition and Option 3. The peaks of the transfer functions indicate a change in the natural frequencies of the primary system as well as a reduction in the amplification values.

The comparison of response spectra calculated for the "as-built status" and for the "upgraded status" (Option 4) are plotted in Figures 18 to 21. Figures 22 and 23 show the implementation schemes of the dampers on the steam generator as well as main pump location.

6 CONCLUSIONS

In order to evaluate the efficiency of the adopted dampers and their location, comparisons were performed on the basis of the results of different upgrading concepts considering the available gap (80 mm horizontal and 40 mm vertical) of the VES 100/40/80 dampers as well as the stabilization effects at the edges of the steam generators. Option 3 (six dampers on the SG and one on the MCP) was selected (Figure 21).

It can be observed that the reduction in the response noted in the case of viscous dampers is not significant but that the main objective of the introduction of viscous dampers was the limitation of the expected displacements and stresses in the RCS loops to the allowable values. This has been achieved.

7 REFERENCES

- [1] PAKS Unit 4, RCS / RBCB, Mathematical (3D) Model for Dynamic Characteristics of the RCS for As-built Conditions, Siemens Work-Report KWU NDA2/96/E0534
- [2] PAKS Unit 4, RCS / RBCB, Structural Dynamic Analysis for Seismic Loading of the Primary System PAKS (As-built Conditions), Siemens Work-Report KWU NDA2/97/E0555
- [3] Criteria and Methodology Specification for Seismic Reanalysis and Upgrading of Buildings and Mechanical Systems of Paks NPP Units 1-4, Siemens Work-Report KWU NDA2/96/0516
- [4] Artificial Acceleration Time Histories for the site PAKS Based on Final Seismological Input Data Paks Units 1, Siemens Work-Report KWU NDA2/96/E0527a
- [5] SASSI, A Computer System for Dynamic Soil-Structure Interaction Analysis, Siemens KWU Version 1/1991 (Original source M. Tabatabaie-Raissi, J. Lysmer, University of California, Berkeley)
- [6] GERB Rohrleitungs-Typenreihe VES, Technischer Bericht July 1997

MODE NR	FREQUENCY (Hz)	RAE DOF	MODALE GEWICHTE			DAERFUNG (%)	
			X1	X2	X3	MODAL	ETA
1	0.31	5290-2	322.9	4797.1	0.0	5.00	5.00
2	0.31	5192-2	1916.6	745.2	0.0	5.00	5.00
3	0.31	5484-2	231.5	1031.9	0.0	5.00	5.00
4	0.31	5492-1	2364.5	195.2	0.0	5.00	5.00
5	0.31	5192-1	423.0	514.9	0.0	5.00	5.00
6	0.31	5590-2	319.7	533.1	0.0	5.00	5.00
7	1.33	5490-2	3.4	5333.7	0.2	5.02	5.02
8	1.34	5493-1	5088.4	0.0	0.4	5.02	5.02
9	1.35	5383-2	132.3	3.2	0.0	5.00	5.00
10	1.35	5393-1	2.4	24.6	0.0	5.00	5.00
11	1.55	5693-1	9.4	45.4	0.0	5.00	5.00
12	1.59	5245-1	14.1	4.5	0.0	5.00	5.00
13	2.87	5010-2	374.4	21749.1	4.9	5.18	5.18
14	2.87	5010-1	26870.1	357420.9	113.6	18.55	18.55
15	2.87	5010-1	3165.8	206767.7	339.0	7.32	7.32
16	2.15	5010-1	1742659.7	309645.0	4307.4	10.33	15.00
17	2.50	5010-1	252172.4	180910.1	38.5	21.14	15.00
18	2.26	5010-2	224.3	46093.1	8850.9	6.36	6.36
19	2.37	5084-1	21.3	545.4	46.4	5.02	5.02
20	3.37	5100-1	118.0	5332.1	1055.2	5.21	5.21
21	3.28	5084-3	3.5	1486.1	82.1	5.04	5.04
22	3.39	5010-3	158.5	1278.1	100.2	5.03	5.07
23	3.39	5010-1	73.0	2876.8	2330.0	5.16	5.24
24	3.49	5010-2	5469.6	108027.4	17820.2	14.35	16.75
25	3.78	5010-2	18281.4	12942.0	1839594.7	54.95	10.00
26	4.28	5462-1	44.1	44.3	8.5	5.01	5.01
27	4.29	5692-1	44559.1	189.6	18332.4	4.31	9.31
28	4.31	5582-1	359.1	11.4	294.8	5.04	5.04
29	4.31	5462-2	155533.0	238.7	64924.5	14.29	15.00
30	4.59	5248-2	19.7	78.3	56.8	5.04	5.04

Tab. 1 Eigenfrequencies of the RCS and RBCB System

Structure	Modal Point	Displacements (mm)		
		X	Y	Z
RPV	5D1 5D-0	2.2	0.0	0.3
Valve / CL	-C2	78.2	80.8	2.3
Valve / HL	-C3	80.0	78.5	14.3
Steam generator	-R0	186.5	172.8	4.3
	-R1	120.3	129.0	2.8
	-R2	192.0	203.5	5.2
	-R3	127.4	145.2	3.1

Tab. 2 Maximum Relative Displacements As-Built Conditions (Alternative 0)

Alternative	Displacements (mm)		
	X	Y	Z
0 (# = 0)	182.9	172.8	4.3
1 4 = 0	56.2	83.0	6.7
2 4 = 1	89.3	62.3	6.7
3 5 = 1	66.5	60.2	8.5
4 8 = 1	52.0	53.7	6.4

Tab. 3 Maximum Relative Displacement of the Steam Generator Grid in Relation to the Supporting Rack

Region	Alternative	Forces [kN]			Moments [kNm]		
		P1	P2	P3	M1	M2	M3
RPV	0	1000	180	220	200	1700	960
	0+0	1900	170	260	170	1800	810
SG	0	23	560	240	1900	360	730
	0+0	1700	150	270	190	1100	160
MCP	0	1000	170	160	30	600	600
	0+0	3000	230	53	120	100	490
RPV	4	1400	170	170	-9	410	650
	8-1	1400	160	110	64	500	590
SG	3	14	210	100	620	170	332
	8-1	1200	100	100	41	620	120
MCP	4	400	420	32	260	210	
	8-1	300	270	25	55	57	290

Tab. 4 Maximum Forces [kN] in Characteristic Regions of the RCS Nozzles of RPV (Cold/Hot Leg)

Region	Alternative	N.O.L. ²			Seismic			Seismic-Dead Load		
		P	T ⁿ	A	B	C	A	B	C	
RPV	0 0+0	1	101	1	34	103	256	34	103	306
		2	101	7	34	103	280	34	103	304
		3	101	7	34	103	280	34	103	304
SG	0 0+0	1	101	15	0.4	104	52	0.4	104	87
		2	101	5	31	10	212	31	10	40
		3	101	10	56	80	70	56	80	140
MCP	0 0+0	1	101	3	17	79	95	17	79	165
		2	101	7	25	78	107	25	78	167
		3	101	10	22	6	94	22	6	94
RPV	4 8+1	1	101	1	25	74	84	25	74	134
		2	101	7	25	78	107	25	78	167
		3	101	10	22	6	94	22	6	94
SG	4 8+1	1	101	5	0.2	47	25	0.2	47	50
		2	101	15	22	6	94	22	6	94
		3	101	10	6	32	15	6	32	85
MCP	4 8+1	1	101	3	15	26	52	15	26	122
		2	101	7	25	78	107	25	78	167
		3	101	10	6	32	15	6	32	85

Tab. 5 Maximum Stresses [Mpa] in Characteristic Response of the RCS Nozzles of RPV (Cold/Hot Leg)

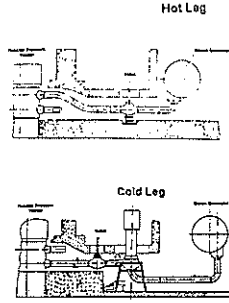


Fig. 3 Constructional Concepts of the Cold and Hot Legs of the Primary System

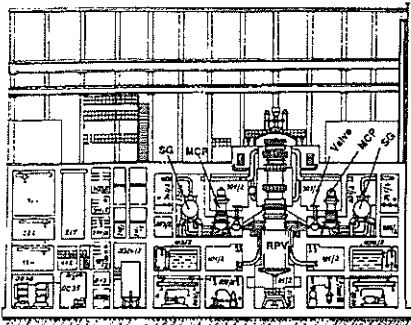


Fig. 1 Arrangement of the Reactor Cooling System in the Concrete Block

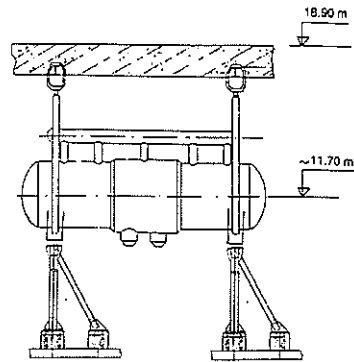


Fig. 4 Constructional Concept of the Steam Generator

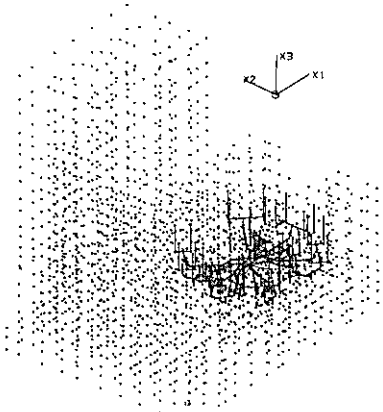


Fig. 2 Interfaces of the Reactor Cooling System and Reactor Building Concrete Block

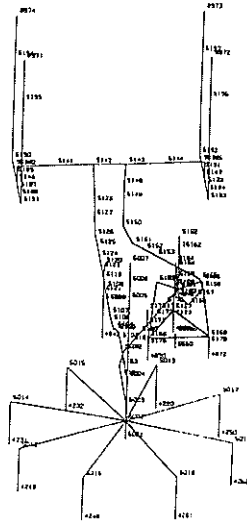


Fig. 5 Mathematical Model of a single Loop

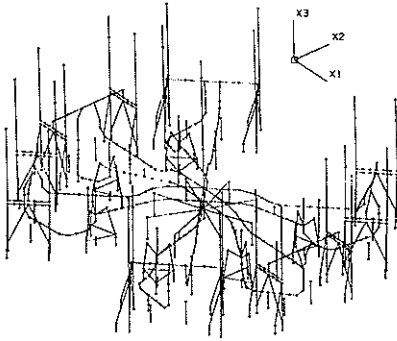


Fig. 6 Mathematical Model of the Complex RCS

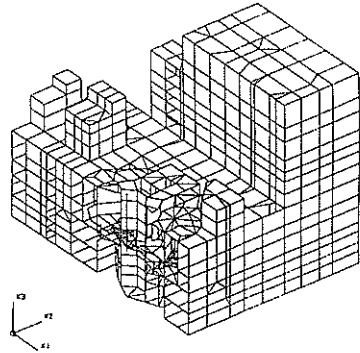


Fig.7 Complex Mathematical Model of RCS and RBCB

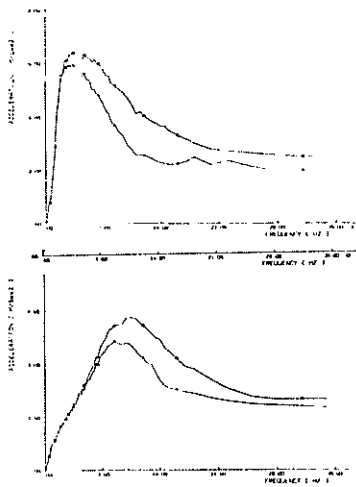


Fig. 8 Free Field Response Spectra for Surface and Foundation Level

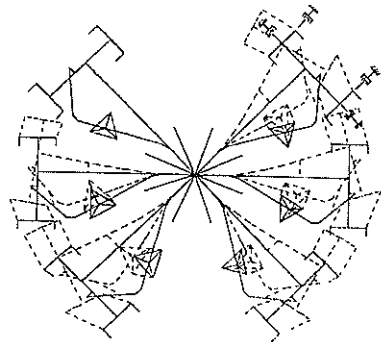


Fig. 9 Mode Shapes and Upgrading Measures on Steam Generators

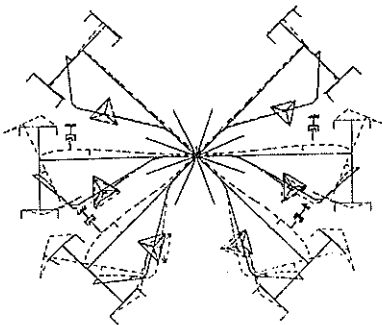


Fig. 10 Upgrading Measures on Hot Legs

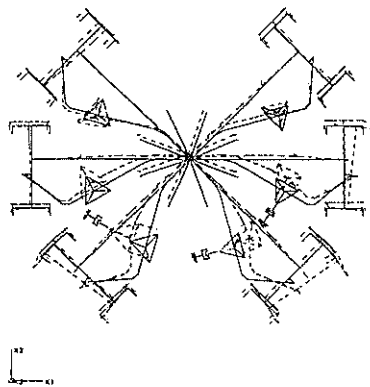


Fig. 11 Mode Shapes and Upgrading Measures on MCP

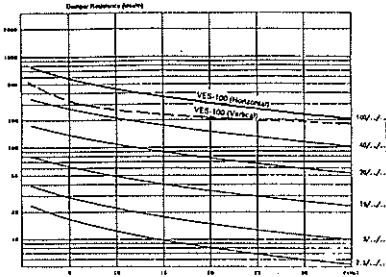


Fig. 12 Frequency Dependent Damper Resistance of GERB Dampers

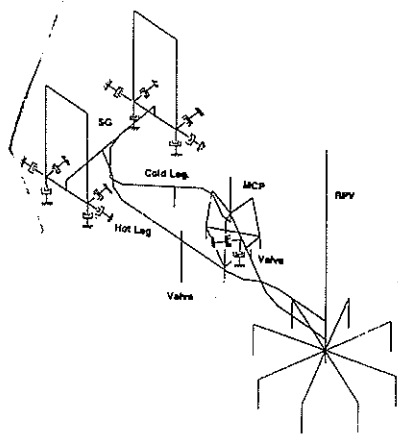


Fig. 14 Retrofit Alternative 2 (4 + 1)

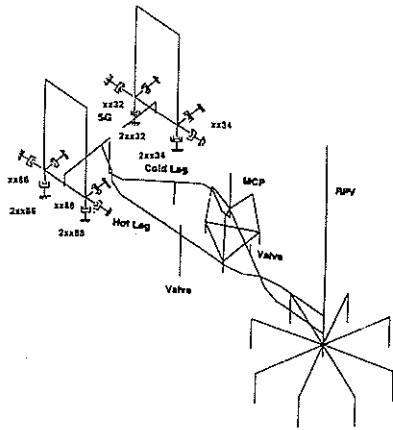


Fig. 13 Retrofit Alternative 1 (4 + 0)

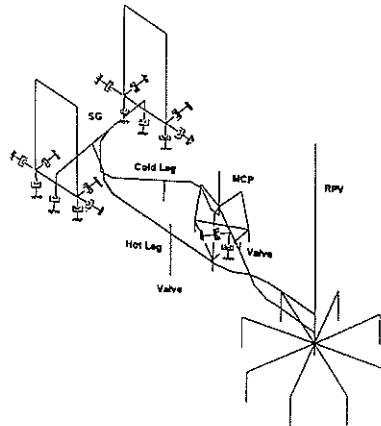


Fig. 15 Retrofit Alternative 3 (6 + 1)

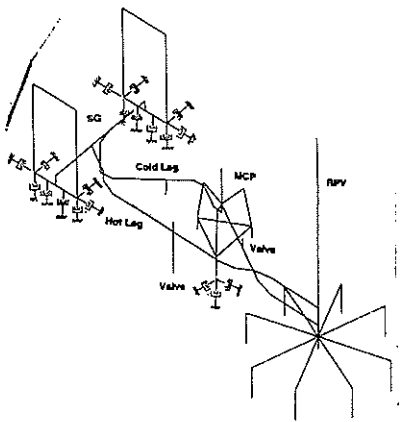


Fig. 16 Retrofit Alternative 4 (8 + 1)

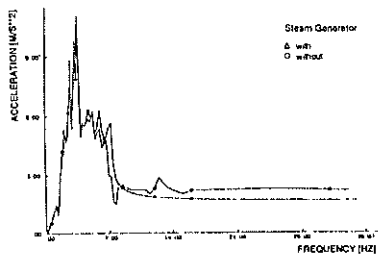


Fig. 21 Comparison of Response Spectra (Alternative No 3) without and with Dampers, Vertical

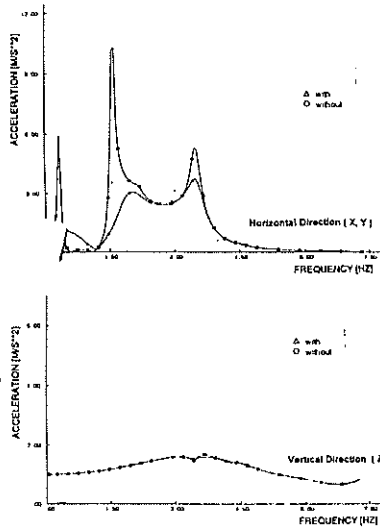


Fig. 17 Comparison of Transfer Functions (Alternative No 3) without and with Dampers ,Steam Generator

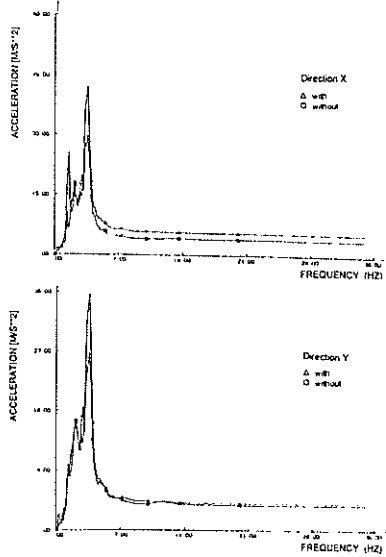


Fig. 18 Comparison of Response Spectra (Alternative 3) without and with Dampers, Steam Generator Nozzles Horizontal Direction

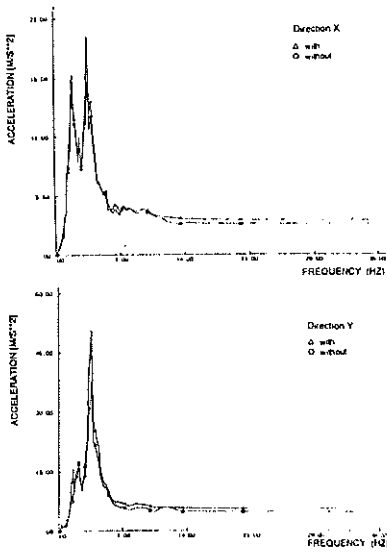


Fig. 19 Comparison of Response Spectra (Alternative No 3) without and with Dampers, Main Cooling Pump Horizontal Direction

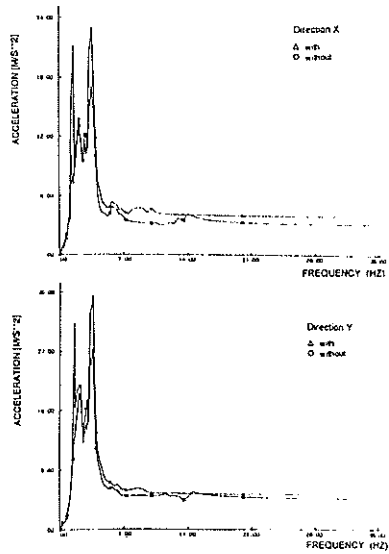


Fig. 20 Comparison of Response Spectra (Alternative No 3) without and with Dampers, Hot Leg Valve Horizontal Direction

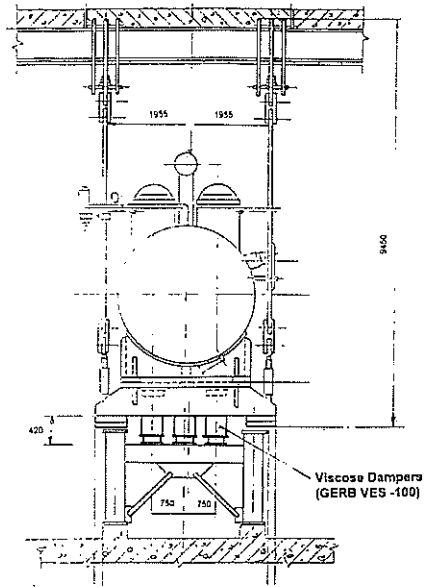


Fig. 22 Implementation of Dampers on Steam Generator Supports (Scheme)

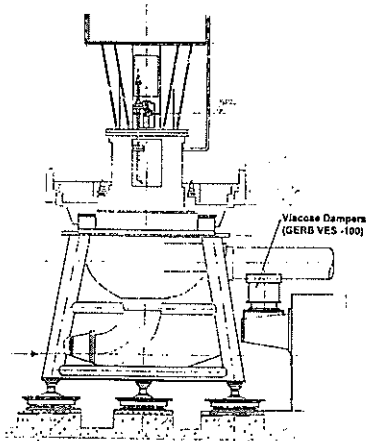


Fig. 23 Implementation of Dampers on Main Cooling Pumps (Scheme)