



Dynamic Characteristics and Structural Response of the SWR 1000 under Earthquake Loading Conditions

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ABSTRACT

Using the basic design documentation as well as specified seismological and soil-dynamic input data as a basis, the dynamic characteristics of the coupled vibrating structure of the design of the SWR 1000 reactor building were analyzed.

The structural design analysis was based on a 3-dimensional mathematical model of the building in which all details of the internal structures as well as the containment including the water in the pools were represented adequately.

In order to demonstrate the soil-structure effects, the soil was represented by two different assumptions on the basis of which the frequency-dependent and frequency-independent impedances were derived.

The structural responses obtained by means of the assumptions for considering the soil-structure effects were evaluated and compared. The suitability of the structural design concept are discussed and the structural response results obtained on the basis of the bearing capacity and the stresses in the characteristic regions of the structure.

INTRODUCTION

The SWR 1000 represents a new, advanced medium-capacity (approx. 1000 MW) boiling water reactor design developed by Siemens AG in conjunction with German electric utilities, and, since 1995, also with the support of European partners (TVO of Finland, KEMA of The Netherlands, PSI of Switzerland and ENEL of Italy).

The design of the SWR 1000 is characterized by the following features:

- Passive safety
- Economic design.

It was possible to implement these two features by simplifying the systems required for plant and operational safety. The SWR 1000 project is currently in its "Basic Design Phase" which started in mid-1995 and is expected to be concluded by the end of 1999 with the issuance of a safety analysis report and an estimate of construction costs. In addition to this development work, which also includes a design review for regulatory compliance, all new passive safety components have been successfully put through full-scale tests on various test rigs in Switzerland and Germany to verify their functional reliability and capacity. The passive core flooding system is still undergoing tests at the Jülich Research Center and the effects of aerosol deposition on the containment cooling condenser are presently being investigated as part of the CONGA Research Program of the European Union. Another series of tests, aimed at verifying the results of analyses carried out of cooling of the RPV exterior in the event of a core melt accident, is still at the planning stage. The present status of development and the results obtained from experimental verification of the new systems

and components show that the design concept of the SWR 1000 will reach commercial maturity by the year 2000.

2 DESCRIPTION OF THE STRUCTURE AND INPUT DATA

The reactor building of the SWR 1000 (Figure 1) comprises a box-shaped outer concrete shielding structure measuring 48.60 m x 40.2 m which is covered by a plain roof and a free-standing internal structure supported on a common concrete slab.

The bottom of the building foundation is located approximately 12.0 m below plant grade. In view of the thickness of the foundation slab, this results in a total height of approximately 58 m, 45.7 m of which are above plant grade.

The outer shielding structure is designed for the aircraft impact and earthquake load cases. It is made of normal reinforced concrete and has a thickness of 1.6 m.

The internal structure (containment) consists of two concentric cylinders made of reinforced concrete (1.0 m) supported by the foundation mat. In the upper region (above 19.4 m) the cylinders are covered by a concrete plate measuring about 1,6 m in thickness. The pools and some of the passive safety systems in the space between the two cylinders which are divided by two floors at elevations -5.30 m and $+8.60$ m as well as a number of radial walls.

The pressure suppression pools are located at elevation -5.30 m while the core flooding pool is at elevation of 8.60 m. The fuel pool is located at approx. $+13$ m in the reactor building on an extension of the axis of the dryer-separator storage pool and reactor well, and extends to elevation $+21.60$ m on the containment side and beyond this level on the side facing the reactor building wall. The service platform and the refueling machine are located above elevation $+26.30$ m.

The reactor building crane is located at approx. 39.20 m, and is supported by the outer shell. The reactor pressure vessel is supported by the inner cylinder at approx. $+6.60$ m. The compartments surrounding of the inner structure (Figure 5) house mechanical and electrical equipment as well as the piping systems. Below inside the inner cylinder above the foundation plate is located a core catcher and the emergency core cooling systems.

In accordance with the criteria set forth in [1], it was necessary to design SWR 1000 for a wide scattering of site-specific soil data as summarized in Table 1. It was assumed that the soil is homogeneous and horizontally layered. In case of a time-domain calculation such a soil may be represented by complex, frequency-independent impedance functions. These functions have been calculated for the six degrees of freedom of the rigid foundation. Embedment of the building in the soil was neglected. The global soil stiffness and damping underneath the reactor building were derived from the impedance functions for the soil conditions: G_{MAX} , G_{AVE} , G_{MIT} (Table 1). The stiffness and the damping of the soil were tuned to the fundamental frequencies of the coupled soil-structure system and were assumed to be frequency independent.

The seismic input data were specified by the criteria set forth in [1] as well as by a set of artificial time histories (Figure 9) derived in accordance with the studies and assumptions related to the EPR design concept [4]. In accordance with [1], the maximum free-field acceleration are fixed at 0.25 g for the horizontal direction and at 0.167 g for the vertical direction.

3 MATHEMATICAL MODEL AND DYNAMIC CHARACTERISTICS

The mathematical model and the degree of discretization were chosen such that the natural behavior of the structure in the relevant frequency range could be computed with good reliability. Considering the geometric shape of the structure and the design stiffening and mass distribution of the SWR 1000 reactor building as well as the frequency content of the seismic excitation, an equivalent 3D-beam model was selected for the calculations (Fig. 7).

The beam model includes the outer structure, the containment, the inner structure and the foundation mat as an entirely connected total system. Derivation of the equivalent

stiffnesses and masses were derived using a computer-supported tools [8] on the basis of input data and assumptions defined for each floor and elevation (Figure 6).

The weights of the structure were represented as lumped masses located in the mass center of the floor or elevation and connected by means of rigid beams to the rigidity center of the corresponding building part. The weight of the fluid in the pools was represented in accordance with [3] by dividing the total masses into a rigid part (which is added to the structure in the pool regions) and the virtual mass (which is coupled by means of equivalent stiffnesses in the upper region of the pools structure).

The eigenvalue extractions were concluded using the STRUDN finite element code [5] of Siemens in which Lanczos eigensolvers modified for solving large matrices are implemented.

The eigenfrequencies and modes were calculated for the static as well as strain-adapted shear modulus summarized in Table 1. The calculated modal values for G_{AVE} are shown in Table 2. The final stiffnesses were obtained by modifying the stiffnesses obtained from the corresponding impedance function in several iterations and by performing additional eigenvalue runs.

For G_{AVE} the fundamental eigenfrequencies are about 2.95 Hz and 3.34 Hz in the horizontal directions X1 and X2 respectively, and about 6.3 Hz in the vertical direction (Figure 8). It was found that the sum of the modal masses up to 25 Hz constitutes about 98 % of the total actual weight, and that therefore the frequency range relevant to the seismic loading condition is adequately enveloped. In case of the time-domain analyses, damping was considered in the form of modal damping. On the basis of the structural characteristics of the building and the soil, the damping values of the individual modes (modal damping) were calculated by applying a weighting function proportional to the deformation energy. In accordance with KTA Safety Standard 2201.3 (Reference [8]), the modal damping values thus obtained were limited to 15 % for horizontal and rocking vibration, and to 30 % for vertical vibration.

4 CHARACTERISTIC RESULTS

In order to evaluate the dynamic response results of the SWR 1000, time-domain calculations were performed by means of frequency-independent stiffnesses and dampings. Modal superposition procedures were performed for the given scattering of soil data as well as for a specified seismic input motion. The results obtained for characteristic regions of the reactor building for all 3 types of soil were compared and evaluated by means of response spectra (2 %) plotted in a single graph (Figures 10 to 18). It can be observed that there is a significant frequency shift in the peak frequency as well as a change in the acceleration in all regions of the structure.

In order to demonstrate the ratio by which the dynamic response results can be reduced when analyzing the structures by means of complex mathematical models taking into consideration the frequency dependency of stiffnesses and dampings. This procedure allows a more realistic consideration of the total damping capacity of the coupled vibrating and interacting soil-structure system. A significant reduction however can be expected for soft or medium soil condition only.

To demonstrate the influence of the above analysis procedures on the dynamic response results, the response spectra obtained (for G_{AVE}) for characterizing regions by means of time and frequency-domain procedures were compared in plotted form (Figures 19 to 24). It can be observed that the design harbors a certain conservatism when assuming the cut-off of damping.

5 CONCLUSIONS

The basis of the calculations performed for the SWR 1000 reactor building was a equivalent mathematical model and sufficiently obtained (by frequency dependent and independent)

soil impedances for the specified values of soil properties. Despite the complexity of the building, the interaction effects between the different substructures and the soil-structure were therefore considered reasonable in the analyses.

The acceleration response spectra obtained represent the scattering of acceleration values which should be expected when evaluating the capacity of the structure and of important components to withstand seismic events. The results obtained for the medium and upper band of the soil parameters G_{MIN} and G_{MAX} are characterized in general by a shift in the peak frequency as well as by changes in the acceleration level. It could be also demonstrated that the results obtained by time-domain analyses are conservative in comparison to results obtained by frequency-domain analyses.

Evaluating the dynamic response results of the advanced SWR 1000 design concept, it can be stated that in the lower part the loading conditions of components and systems are similar or lower (in the horizontal direction) to the conditions known from earlier BWR or PWR designs of Siemens. This is mainly due to the fact that the center of gravity of the SWR 1000 is located at a relatively low level. Although the studies of the structural design do not necessarily represent the final structural design concept, the above comments need to be considered.

6 REFERENCES

- [1] SWR 1000, Schutz der Anlage gegen Einwirkungen von außen (EVA) Arbeits-Bericht NS-P/97/0032
- [2] STABGEN – Programm zur Erstellung von 3D-Balkenmodellen für dynamische Berechnungen, Benutzerhandbuch, Version 1.0, Arbeitsbericht KWU R621/84/0095
- [3] TID – 7024, Nuclear Reactors and Earthquakes United States Atomic Energy Commission Division of Technical Information
- [4] Artificial Time Histories for the Load Case Project: EPR – Basic Design Phase Work-Report KWU NDA2/96/e0016a
- [5] SZTRUDYN, "General Purpose Computer Program for structural Dynamic and Static Analyses", User Information Manual, Siemens VAX Version 5/1991.
- [6] SASSI/Siemens (1981) – A Computer Systems for Analysis of Soil Structure Interaction, User Information Manual, Siemens VAX Version 1/1991
- [7] USNRC Regulatory Guide 1.122, September 1997
- [8] Sicherheitstechnische Regel des KTA, Teil 3, Auslegung der baulichen Anlagen KTA 2201.3

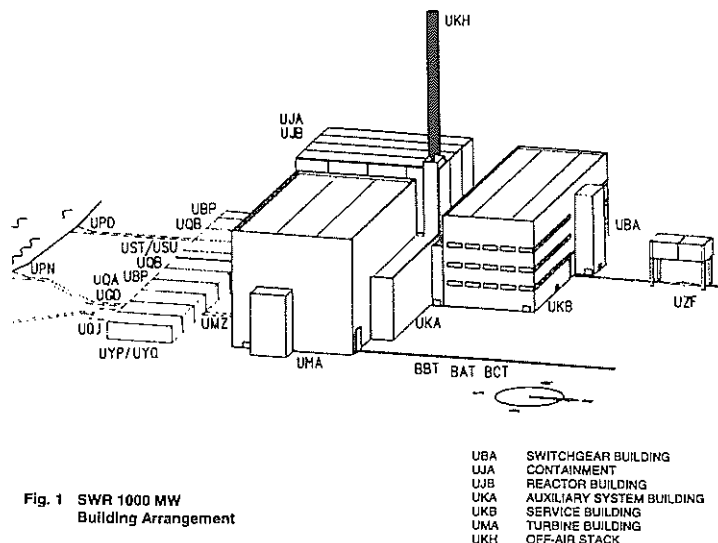


Fig. 1 SWR 1000 MW Building Arrangement

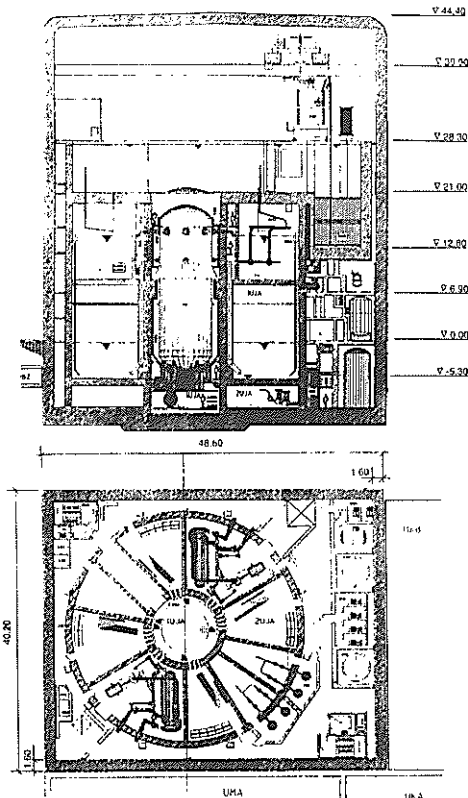


Fig. 2 SWR 1000 MW Constructional Concept, Section

MODE NO	FREQUENCY (Hz)	MAX DEF	MODALE KL	GEWICHTS EZ	ΣZ	DAEMPFUNG (%) MODALE RTA
1	0.13	3890-2	0.4	12897.5	0.0	0.30 0.50
2	0.13	3890-1	33702.2	0.6	152.6	0.50 0.50
3	0.13	3890-3	152.2	0.8	12492.0	0.30 0.50
4	0.14	3780-2	0.4	4377.6	0.9	0.50 0.50
5	0.14	3780-1	8341.2	0.2	97.0	0.50 0.50
6	0.14	3780-3	37.4	1.0	4315.3	0.50 0.50
7	0.14	3780-2	4.0	23612.4	4.9	0.30 0.50
8	0.14	3780-1	23685.8	8.6	331.2	0.50 0.50
9	1.16	3300-3	721.5	0.5	23344.8	0.30 0.50
10	0.27	3400-2	1.0	4402.4	0.2	0.50 0.50
11	0.27	3400-1	3410.0	0.4	973.7	0.50 0.50
12	0.27	3400-3	976.1	0.8	3376.1	0.30 0.50
13	1.95	370-2	32.4	744480.8	0.1	13.14 13.04
14	1.95	370-1	794765.3	35.6	180.2	14.43 14.43
15	1.95	3400-3	1.5	59495.5	0.7	7.92 7.92
16	5.15	2450-1	42841.4	3.8	5845.5	7.94 7.84
17	4.43	2370-2	14.3	302.6	0.9	8.32 8.32
18	4.43	2370-1	2100.3	28.5	10374.2	46.30 36.00
19	7.61	2370-2	1503.1	18.3	18.3	8.31 8.31
20	8.39	2370-1	16.9	9464.2	1.7	7.49 7.49
21	8.43	2450-1	131165.6	4426.2	1803.6	16.37 14.37
22	8.33	2370-1	6296.4	21321.4	3.5	21.33 13.00
23	7.86	2450-1	137491.1	1040.3	40.7	16.38 13.00
24	11.39	2370-1	182.1	1330.8	0.3	7.38 7.38
25	14.41	2370-3	745.9	754.8	2970.3	7.34 7.34
26	14.27	2450-2	74.4	11241.8	1.7	6.49 6.49
27	14.42	2370-2	28.2	772.7	449.1	7.39 7.39
28	14.42	2450-2	2.8	641.8	1.9	7.40 7.40
29	17.54	2450-1	1923.6	1.3	2591.7	8.25 8.25
30	14.29	2450-2	8.2	61.8	14.4	7.35 7.35
31	28.78	2450-2	2.4	0.6	3.1	7.45 7.45
32	19.01	2450-1	3513.5	0.3	14.5	6.15 6.15
33	21.78	2450-1	1712.2	4000.1	1300.9	10.31 10.21
34	32.15	2450-1	9245.2	3932.3	1344.2	10.16 10.29
35	33.69	3500-3	198.1	61.4	119.5	7.18 7.18
36	21.91	2370-3	2489.4	542.0	1637.8	8.27 8.27
37	33.77	2340-3	1435.9	217.3	4235.8	6.85 6.85
38	35.28	2450-1	1.2	11.9	244.2	7.22 7.22
39	24.01	1300-3	21.3	0.2	4233.4	6.83 6.83
40	27.42	3340-3	157.4	430.9	918.8	7.88 7.89
41	27.95	2450-2	30.6	3739.2	34.4	6.14 6.14
42	28.14	1300-2	0.8	0.0	114.2	7.13 7.13
43	30.16	2450-2	0.7	1.4	6.8	7.11 7.11
44	31.64	2450-2	85.5	13.7	11.7	7.10 7.10
45	32.41	2450-1	1444.3	19.6	15.3	6.51 6.51
46	53.39	2450-2	2.4	324.6	0.3	7.43 7.43
47	34.13	2450-1	135.8	0.0	23.5	7.33 7.33
48	34.20	2450-1	132.4	40.4	7.4	7.33 7.33
49	34.78	2450-3	143.3	40.3	6.3	7.23 7.23
50	34.82	2450-2	49.7	0.3	1.5	7.08 7.09
51	38.13	2450-2	0.8	724.6	1.5	7.24 7.24
52	37.47	1300-2	0.3	24.2	0.4	7.03 7.03

Tab. 2 SWR 1000 MW, G_{ave} Eigenvalues

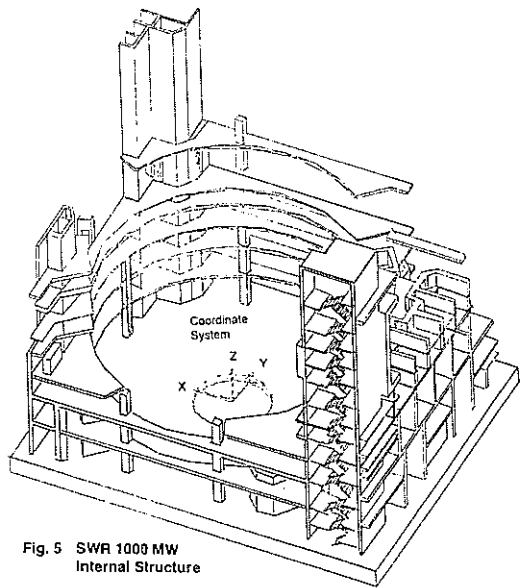


Fig. 5 SWR 1000 MW Internal Structure

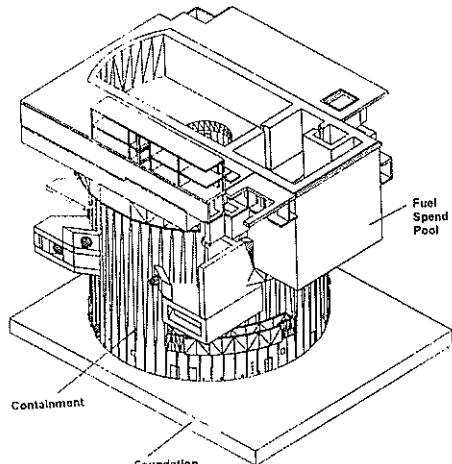


Fig. 4 SWR 1000 MW Reactor Section

	G-Min	G-Average	G-Max
Shear Modulus (GPa)	500	1408	3400
Poisson Ratio	0.47	0.40	0.35

Translational Direction						
Direction	Stiffness (kN/m)	Damping (%)	Stiffness (kN/m)	Damping (%)	Stiffness (kN/m)	Damping (%)
X	64.6E+06	63	182.0E+06	45	443.0E+06	70
Y	64.6E+06	60	182.0E+06	40	439.0E+06	70
Z	37.6E+06	80	243.0E+06	65	580.0E+06	50

Rotational Direction						
Direction	Stiffness (kNm/r)	Damping (%)	Stiffness (kNm/r)	Damping (%)	Stiffness (kNm/r)	Damping (%)
XX	37.9E+09	10	93.0E+09	10	232.0E+09	10
YY	52.9E+09	10	121.0E+09	10	312.0E+09	10
ZZ	60.9E+09	10	139.0E+09	10	352.0E+09	10

Tab. 1 Scattering of Soil Data and Frequency Independent

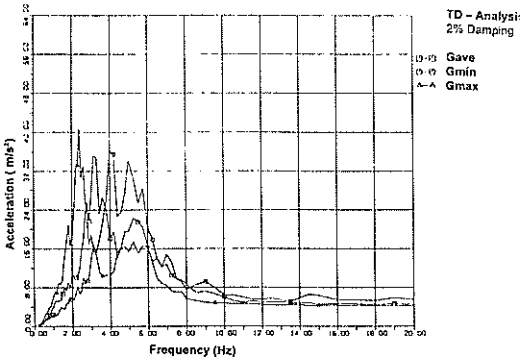


Fig. 13 SWR 1000 MW, Dynamic Response on Top of Reactor Section Comparison of Results Gmin/Gmax/Gave , Direction X1

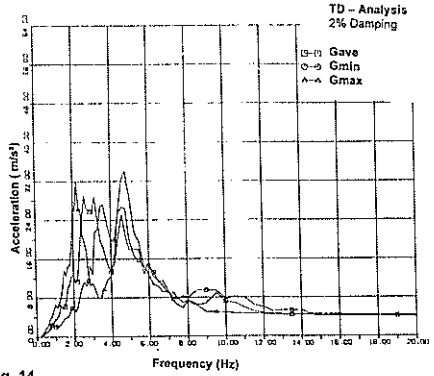


Fig. 14 SWR 1000 MW, Dynamic Response on Top of Reactor Section Comparison of Results Gmin/Gmax/Gave , Direction X2

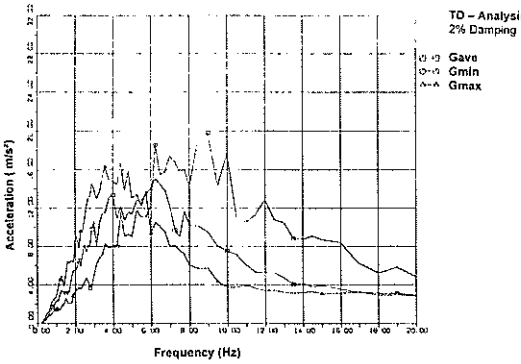


Fig. 15 SWR 1000 MW, Dynamic Response on Top of Reactor Section Comparison of Results Gmin/Gmax/Gave , Direction X3

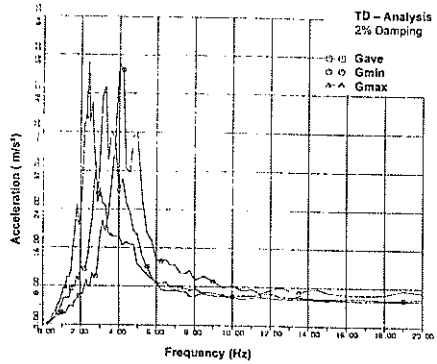


Fig. 16 SWR 1000 MW, Dynamic Response on Top of Reactor Building Comparison of Results Gmin/Gmax/Gave , Direction X1

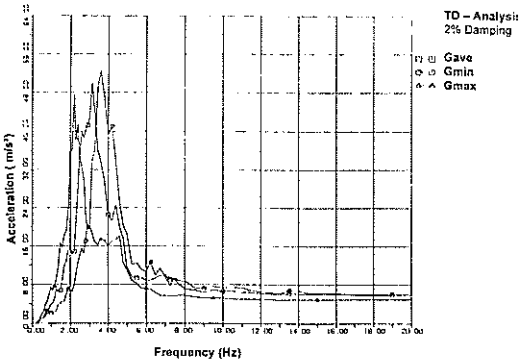


Fig. 17 SWR 1000 MW, Dynamic Response on Top of Reactor Building Comparison of Results Gmin/Gmax/Gave , Direction X2

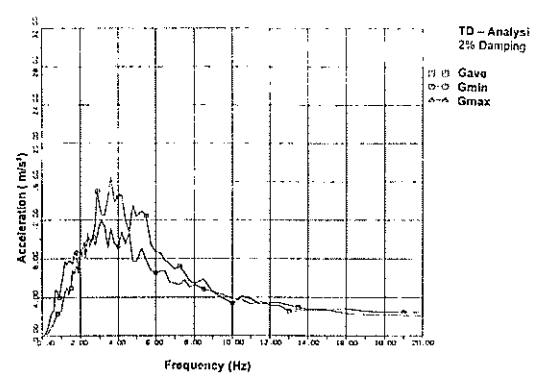


Fig. 18 SWR 1000 MW, Dynamic Response on Top of Reactor Building Comparison of Results Gmin/Gmax/Gave , Direction X3

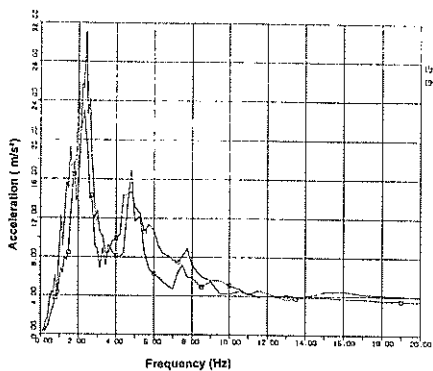


Fig. 19 SWR 1000 MW, Dynamic Response on Foundation Mat Comparison of Results Time/Frequency Domain , Direction X1

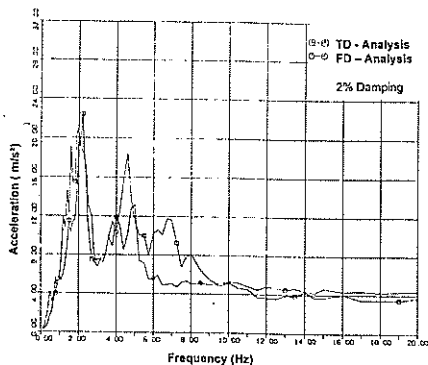


Fig. 20 SWR 1000 MW, Dynamic Response on Foundation Mat Comparison of Results Time/Frequency Domain , Direction X2

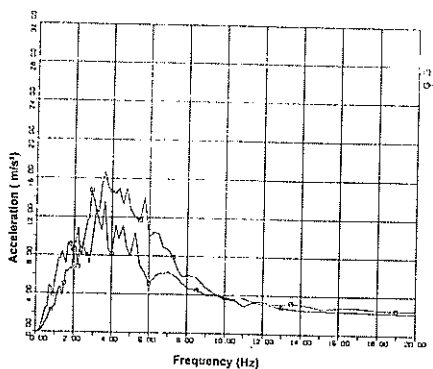


Fig. 21 SWR 1000 MW, Dynamic Response on Foundation Mat Comparison of Results Time/Frequency Domain , Direction X3

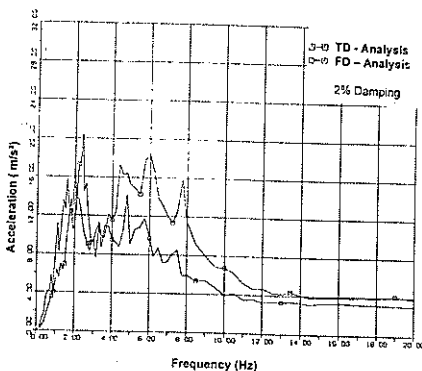


Fig. 22 SWR 1000 MW, Dynamic Response on RPV Support Level Comparison of Results Time/Frequency Domain , Direction X1

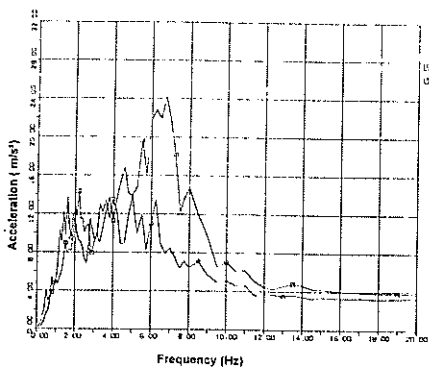


Fig. 23 SWR 1000 MW, Dynamic Response on RPV Support Level Comparison of Results Time/Frequency Domain , Direction X2

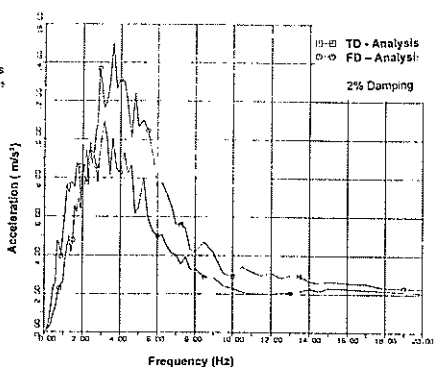


Fig. 24 SWR 1000 MW, Dynamic Response on RPV Support Level Comparison of Results Time/Frequency Domain , Direction X3