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Seismic Design of the ABB-CE System 80+ Standard Plant for a Site Envelope

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ABSTRACT

This paper provides a summary of the design parameters used in the seismic design of the ABB Combustion Engineering (ABB-CE) System 80+ Standard Plant. The System 80+ seismic design was developed with the objective of achieving a standard design which would have a seismic capacity enveloping the seismic demand for the majority of sites in the world with the possible exception of sites near major active faults in areas of known high seismicity. The seismic design basis was developed based on the current state-of-the-art as well as consideration for both current and anticipated future Nuclear Regulatory guidance. The paper discusses seismic design requirements, selection of generic soil sites, selection of design control motions, soil-structure interaction analyses, and site acceptance criteria for the plant. The seismic design process used for System 80+ results in a demonstrated seismic capacity which exceeds the requirements set for current Advanced Light Water Reactor (ALWR) designs.

Introduction

The ABB Combustion Engineering System 80+ Standard Design is a standardized design based on proven technology to provide the certainty and confidence for a safe, reliable, and economical energy option. It has evolved from a proven ABB Combustion Engineering System 80 standard design and has been expanded to encompass the complete plant with the exception of a few site-specific structures/systems. The design is described in detail in the System 80+ Standard Plant Design Control Document (DCD) (Reference 1). The design has been reviewed by the United States Nuclear Regulatory Commission (USNRC) under the 10 CFR 52 Standardization Rule and certified and licensed as a standard design for use in nuclear plants.

The seismic design of the System 80+ structures, systems, and equipment is based on design criteria that are described in this paper. An overview of the criteria related to the basic seismic parameters and methodologies is presented, i.e., the earthquake ground motions, the soil profiles, the seismic analysis methodology, and the site acceptance criteria.

Description of the System 80+ Nuclear Island

The System 80+ Nuclear Island consists of the Reactor Building and the Nuclear Annex, both founded on a ten (10) foot thick common basemat. The top of the Nuclear Island basemat is located approximately 40.75 feet below the finished grade elevation. The Nuclear Island structures house, protect, and support plant equipment and provide personnel and equipment access, support for systems and components under operating loads, radiation shielding, structural components to withstand loads due to design basis external and internal events, physical separation between divisions of safety- related equipment, and barriers to minimize or prevent the release of radioactive materials. The Nuclear Island and adjacent turbine and radwaste buildings are depicted in Figure 1.

The reactor building is composed of the containment shield building, the steel containment including the internal structures, and the subsphere. The shield building is a reinforced concrete right cylinder with a hemispherical dome which encloses the containment and is structurally connected to the nuclear annex. There is an annulus between the containment and the shield building. The reactor building subsphere is located below the containment and the reactor building annulus and is divided by a divisional wall. Within the subsphere each division is further divided into quadrants. The structural components of the subsphere are structurally connected to the shield building and support the containment and containment internal structures.

The containment is a spherical welded steel structure supported by embedding a lower segment between the containment internal structures concrete and the reactor building subsphere concrete. There is no structural connection between the free-standing portion of the containment and adjacent structures other than penetrations and their supports. The containment internal structures are reinforced concrete and structural steel structures that support the reactor vessel, reactor coolant system, and polar crane.

The nuclear annex surrounds the reactor building, is divided by a divisional wall, and consists of the control complex, diesel generator areas, fuel handling area, spent fuel storage area, chemical and volume control system and maintenance area, and main steam valve houses. The nuclear annex is a reinforced concrete and structural steel structure which is structurally connected to the shield building.

The reactor building and annex building and their respective sub-areas are shown in Figure 2.

Earthquake Ground Motions

Three separate control motion spectra, described below, were developed to cover a maximum range of possible sites where the System 80+ standard design may be constructed. The control motion design response spectra are anchored to a 0.3g peak ground acceleration and were developed with the objective of being in full compliance with NUREG-0800 (Reference 2) guidance as well as the EPRI ALWR Utility Requirements Document (URD) (Reference 3).

a. Control Motion Spectrum 1 (CMS1): This spectrum is a soil spectrum identical to Regulatory Guide, 1.60 (R.G. 1.60) [Reference 4] Spectrum. It is considered in order to cover sites with deep soil deposits.

b. Control Motion Spectrum 2 (CMS2): This is a rock outcrop spectrum and is developed to cover sites typical of eastern North America which could be subjected to earthquakes with high frequency content.

c. Control Motion Spectrum 3 (CMS3): This is a rock outcrop spectrum and is developed based on recommendations of NUREG/CR-0098 [Reference 5] primarily to cover lower frequency motions w3hich may not be covered by CMS2. In addition, it is in full compliance with NUREG-0800, Section 2.5.2.6, Item 3, for "scaling the acceleration, velocity and displacement values by appropriate amplification factors." It is also enhanced with respect to NUREG/CR-0098 in the high frequency range to cover earthquakes with high frequency content. The maximum spectra acceleration range is extended to 15 Hz, as opposed to 8 Hz which is used in NUREG/CR-0098 motions.

All of the above Control Motion Spectra are shown in Figure 3. CMS2 and CMS3 are applied at the rock outcrop, and CMS1is applied at the free-field ground surface. All three motions are applied to each of the selected soil sites to conservatively cover all combinations. Figures 4 and 5 provide schematic representations of how the control motions are applied in the System 80+ Soil Structure Interaction (SSI) analyses.

Soil Profiles

To cover a maximum range of possible site conditions where the System 80+ design may be constructed, a range of generic site conditions was selected. A total of 13 cases were developed corresponding to 12 soil cases and one rock case. Since each potential site has unique seismic response characteristics, the investigation and selection of multiple generic sites for design purposes required the consideration of resonance between the building structures and the site soil strata. The sites selected for the SSI analyses have free-field amplifications that cover a broad range of frequencies with which fundamental structural frequencies may coincide. Hence, the envelope of the results provide the maximum seismic response to the SSE motions when the plant is founded on soil sites that are bounded by the selected soil profiles.

Generic soil sites were selected by first choosing four generic site categories. These categories were chosen to represent total thicknesses of soil overlying bedrock of 52 feet, 100 feet, 200 and 300 feet.

Nine soil cases were initially selected for evaluation. Upon examination of the results of the response analyses for these cases, three additional cases were added. The latter cases were selected to properly and conservatively cover the response at frequencies that did not seem to be adequately covered by the other analysis cases. A shear wave velocity distribution with depth was selected to provide a reasonably wide range and also to provide significant contrast in velocities at certain depths for a selected number of cases.

An envelope of soil profiles, expressed in terms of shear wave velocity is shown in Figure 6.

Seismic Model Development

The Reactor Building (RB) and Nuclear Annex (NA) for System 80+ consist of the following structures:

Interior Structure (IS)

Shield Building (SB)

Steel Containment Vessel (SCV)

Fuel Storage Area (FS)

CVCS/Maintenance Area (CVCS)

Diesel Generator Areas 1 and 2 (DG-1 and DG-2)

Control Room Areas 1 and 2 (CAA and CAB)

Emergency Feedwater Tank Areas 1 and 2 (EFW1 and EFW2)

The modeling approach that was used for the RB and NA structural model consisted of developing a 3-D finite element model (FEM) and based on the FEM model, developing equivalent 3-D lumped parameter stick models. This approach was used for all structures except the SCV. Because of its slenderness, the Steel Containment Vessel (SCV) has significant "membrane-type" action when it vibrates, and it was explicitly modeled with shell elements.

The Interior Structure stick model section properties were adjusted to dynamically tune the stick model to match the dynamic characteristics of a 3-D finite element model of the complete Interior Structure. Mode shapes, natural frequencies, and mass participation of the predominant modes of vibration were matched.

The shear and cross sectional areas, and moments of inertia were adjusted until a good match was obtained in the horizontal direction and then necessary adjustments were made to the vertical areas.

The concrete shield building stick model was tuned to capture the predominant frequencies, mode shapes, and mass participation determined from an axisymmetric finite element model. The stick model properties were adjusted on the following basis:

> The cross sectional area was reduced in the dome to account for vertical displacement caused by bending of the dome.
>
> The shear areas in the dome were increased to account for the fact that the cross sectional area of a plane cut through the dome is greater than the radial cross sectional area.
>
> The moments of inertia were decreased as the shear areas were increased.

Using the above as guidelines, the shield building stick model properties were adjusted until a good match of dynamic properties with the finite element model was reached.

The Nuclear Annex consists of vertical walls and slabs that are regular shaped and do not exhibit any unusual dynamic characteristics. Therefore, no dynamic tuning was done for the Nuclear Annex stick models.

The FEM of the IS was developed by defining major floor elevations and major elevations at which significant stiffness discontinuities occur across the entire area of the structure. Twelve such elevations were selected, as follows:

+50.00 ft.	Top of Basemat
+68.50 ft.	Second Floor (Center of Slab)
+90.25 ft.	Third Floor (Center of Slab)
+104.50 ft.	Steam Generator Supports
+114.00 ft.	Fourth Floor (Center of Slab)
+120.00 ft.	Top of Reactor Vessel
+144.50 ft.	Operating Floor
+164.33 ft.	Main Steam Line Supports
+178.00 ft.	Top of Steam Generator Shield Walls
+191.33 ft.	(stiffness discontinuity)
+210.00 ft.	Top of Crane Wall

The load-resisting elements of each floor consist of concrete walls. These walls were modeled with quadrilateral shell elements or solid 8-node elements depending on the thickness of the walls. Concrete slabs of significant thickness were modeled with quadrilateral shell elements.

The translational mass and mass moments of inertia were lumped at the center of mass of each floor. This was done for ease of comparison between the full 3-D FEM and the equivalent 3-D stick model. The mass of each floor includes the mass of concrete walls, concrete slabs, concrete columns, heavy steel platforms, and heavy equipment. For light equipment, secondary structural steel, piping, tanks and miscellaneous mechanical and electrical components, a cumulative uniformly distributed mass was estimated and added to each floor.

Since the SB is symmetric about the vertical axis of the RB, the FEM of the SB was developed using an assembly of axisymmetric shell elements. Fixed-base modal analyses were performed for the horizontal and vertical directions and, based on these analyses, mass and stiffness properties were selected for the SB stick model. The mass of the SB was lumped at eleven nodal points along the height of the stick.

The SCV was modeled with shell elements. The bottom nodes, corresponding to elevation +91 ft., were connected with rigid links to the stick model of the IS.

The FB, CVCS, DG, EFW and CA stick models were developed following the procedure used in the development of the IS stick model. Each floor of each area was modeled with finite elements representing the main structural load-resisting elements of that floor. Subsequently, based on these models, equivalent stiffness properties were computed for each floor which were assigned to an equivalent beam element representing that floor in the stick model of that area.

The combined model of the RB and NA structures was generated by linking the individual stick models of all the areas in the NI and NA complex. In addition, the dynamic model of the NSSS was coupled to the IS stick model at the appropriate elevations. Because of the in-plane rigidity of the slabs, all sticks were connected with rigid links at each major elevation, as shown typically in Figure 7. The rigid links provide in-plane rigidity only.

The previous discussion of the models developed for horizontal excitation applies to vertical excitation model development, with minor changes in the case of the IS, FB, EFW, DG, CVCS and CA models. The only difference between the horizontal and vertical analysis stick models is the eccentricity of the center of mass to the center of rigidity at each major elevation.

Seismic Analysis

Two different types of analysis methodologies were used for the seismic analyses for the Nuclear Island. For the fixed-base cases, modal superposition time history analysis were performed using the three control motions (CMS1, CMS2, and CMS3) corresponding to rock site conditions. When a structure is supported on soil, the SSI is taken into account by coupling the structural model with the soil medium. To accomplish this, the methodology of the computer program SASSI (System for Analysis of Soil Structure Interaction, [Reference 6] was used.

The soil-structure interaction analyses were performed using the substructure method formulated in the frequency domain using the complex response method and the finite element technique. The methodology of the computer program SASSI was used with a modified approach to compute the impedance and scattering of the soil/foundation system. A brief summary of the method is described below.

In a sub-structuring method, the soil strata and half space are analyzed first in the frequency domain. From this analysis, the impedances at the soil-structure interface are established.

Subsequently, the impedances are combined with a model of the superstructure, the control motion is applied to the combined system, and the equations of motion are solved for computation of final accelerations and displacements.

For the System 80+ analyses of the Nuclear Island, a modified SASSI methodology was used, which reduced the solution of the SSI problem to three steps:

> Solution of the site response problem to determine the free-field motions within the embedded part of the structure.
>
> Evaluation of the foundation impedances.
>
> Solution of the structural problem. This involved forming the complex stiffness matrices and load vector and solving the equations of motion for the final accelerations.

Figures 4 and 5 show schematic diagrams of the SSI analysis process. For the analysis using the CMS2 and CMS3 motions, the rock outcrop motion (R) was convolved through the soil media to produce the surface motion (S) and foundation level motion (F). The computed surface motion (S) was applied as the control motion in the SASSI SSI model at the free-field ground surface. For the CMS1 analysis, the CMS1 motion was applied directly at the free-field ground surface.

Analytical Results

Analyses for all three control motions and all soil conditions were three dimensional, with input excitations provided in all three orthogonal directions simultaneously. For design purposes, the in-structure response spectra developed for design of systems, subsystems, and equipment were broadened by +15% and smoothed in accordance with Regulatory Guide 1.122. All System 80+ Standard Plant structures, systems, and components are designed for the envelope of soil profiles and seismic excitations defined by the design bases requirements.

Acceptance Criteria

Acceptance criteria for future construction sites were established. The acceptance criteria aim at minimizing additional analysis tasks required in order to demonstrate the adequacy of a selected site. The acceptance criteria were divided in two categories: those related to the seismic excitation motions, and those that are related to the soil characteristics. The fundamental acceptance criterion for the ground motion is that the potential construction site for the System 80+ should be related to a site-specific spectrum that is enveloped by the free field spectra in Figures 3, 8, 9 and 10 at all frequencies. Acceptance criteria are defined separately for rock and soil sites. The fundamental criterion for the soil profile of the potential site is that the soil properties should be bounded by the soil properties considered in the analyses described herein and defined in Figure 6.

Conclusions

The System 80+ Standard Design can accommodate the seismic design requirements for the majority of future nuclear plant sites without design modifications or additional site specific system seismic analyses. The System 80+ Standard Design can accommodate a range of soil conditions and control motions unexceeded in the nuclear industry.

References

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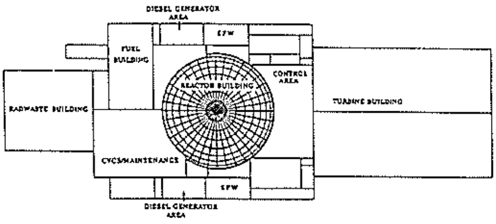
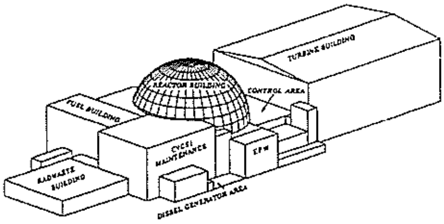
4. Regulatory Guide 1.60, Design Response Spectra for Seismic Design of Nuclear Power Plants", U.S. Nuclear Regulatory Commission, December 1973.

5. Newmark, N.M., Hall, W.J., Development of Criteria for Seismic Review of Selected Nuclear Power Plants", NUREG/CR-0098, May 1978.

6. Lysmer, J., Tabatabaie, M., Tajirian, F., Vahadani, S., Ostadan, F., SASSI A System for the Analysis of Soil-Structure Interaction," Report No. UCB/GT/81-02, Univ. of California, Berkeley, April, 1981.



(a) Plan View



(b) Isometric

Figure 1
Schematic of the System 80+ Standard Design

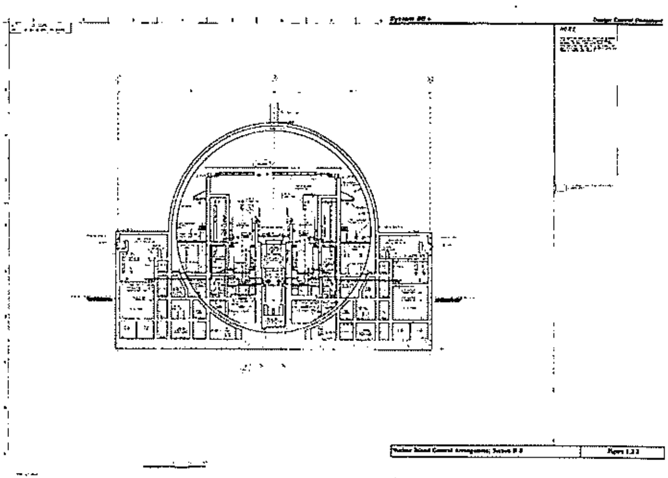


Figure 2

System 80+ Nuclear Island   Section view.

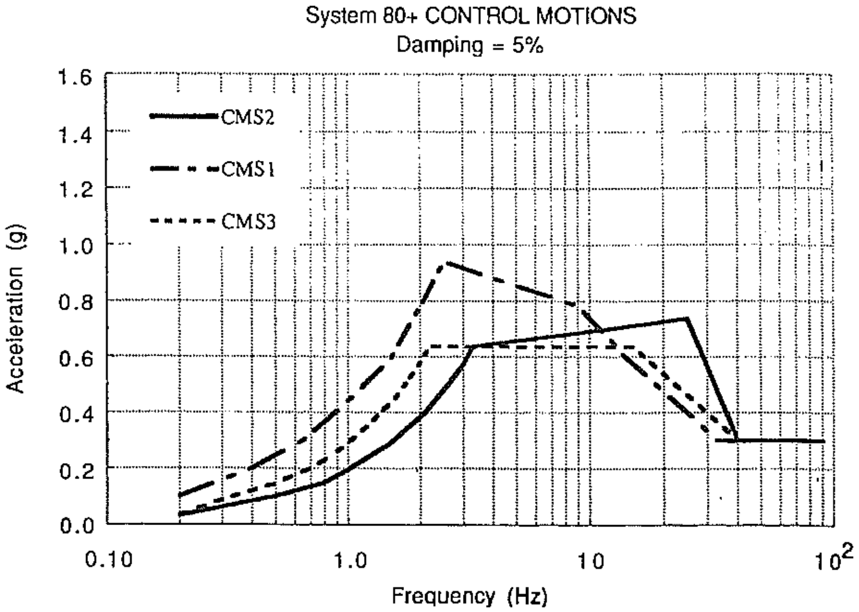


Figure 3
System 80+ Control Motion Spectra

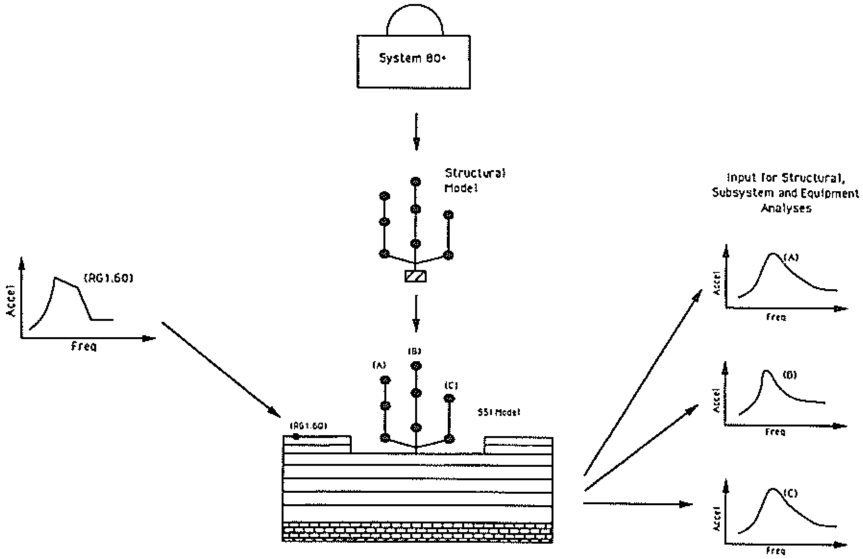


Figure 4
Application of Control Motion Spectra - CMS1 in SSI Ananysis

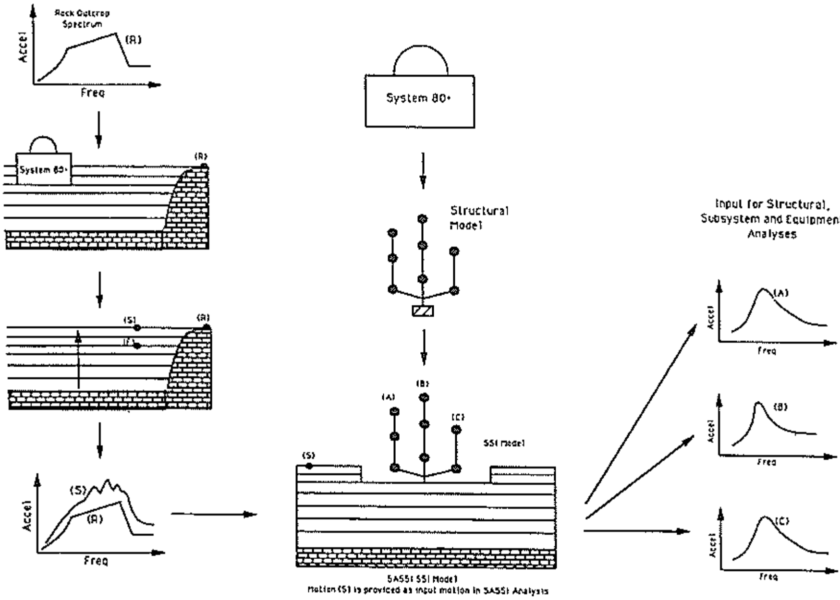
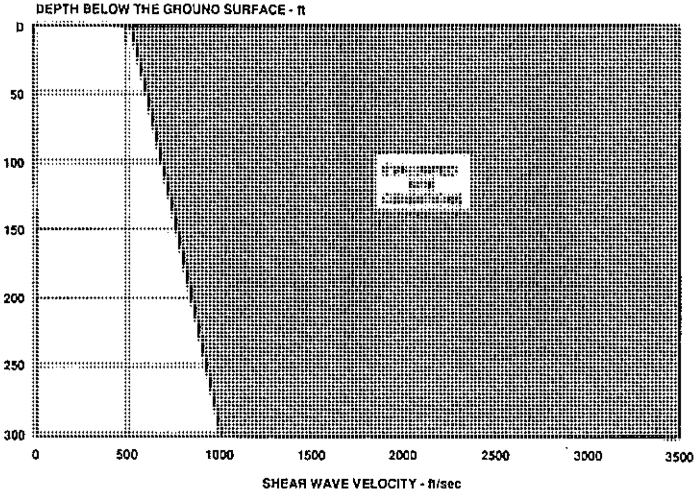


Figure 5
Application of Control Motion Spectra CMS2 and CMS3 in SSI Analyses



NOTE:
FOR SOIL DEPTHS GREATER THAN 300 FEET BELOW GROUND SURFACE,
USE LINEAR EXTRAPOLATION OF THE SHEAR WAVE VELOCITY

Figure 6
Range of Shear Wave Velocities for all Cases Considered

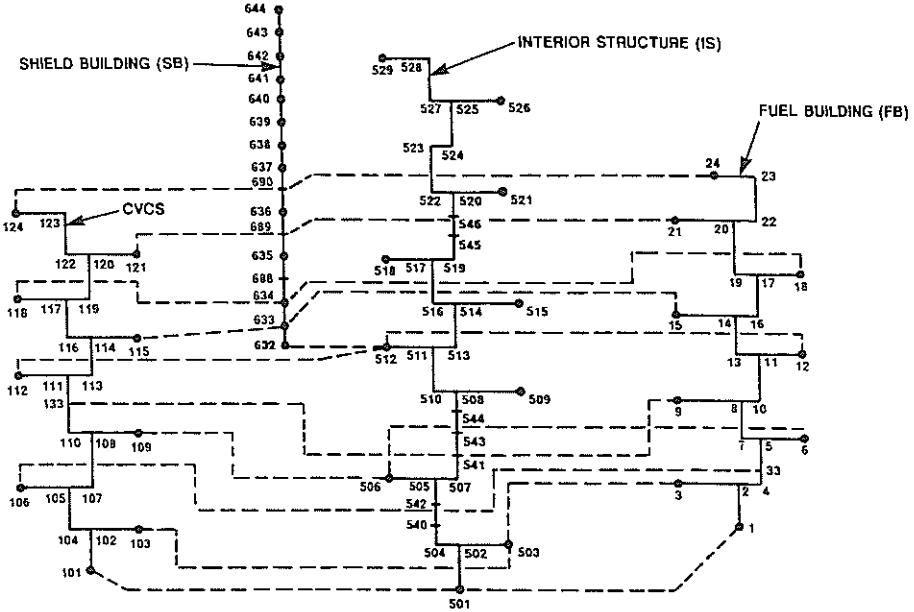
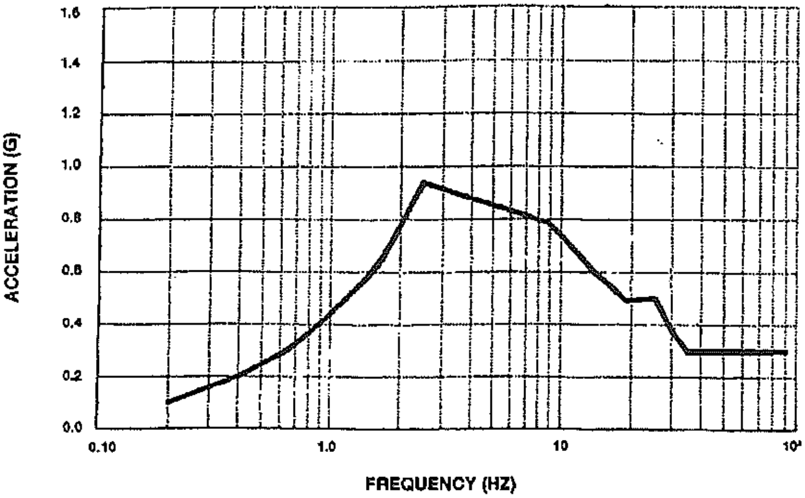


Figure 7
Schematic Diagram of Interior Structure, Shield Building, FB, CVCS

Horizontal Spectrum

DAMPING FACTOR - 5%



Vertical Spectrum

DAMPING FACTOR - 5%

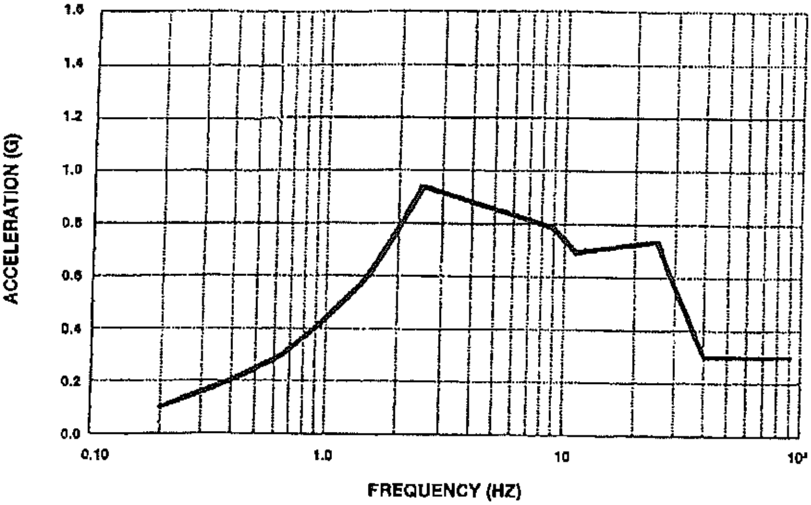


Figure 8
Horizontal and Vertical Free Field Spectra at Foundation Level Rock Sites

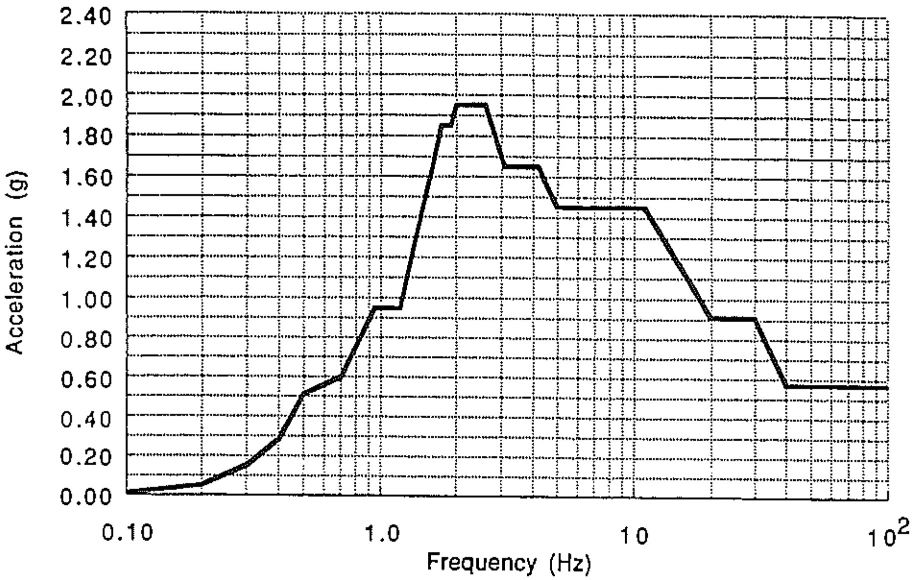


Figure 9
Envelope of Free-Field Surface Spectra Horizontal Motion Soil Sites
(5% Damping)

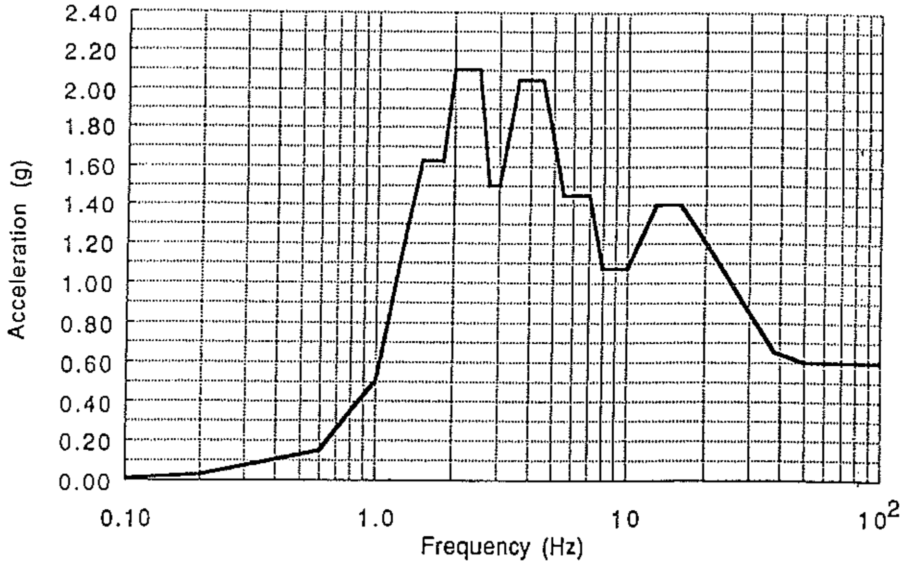


Figure 10
Envelope of Free-Field Surface Spectra Vertical Motion Soil Sites
(5% Damping)