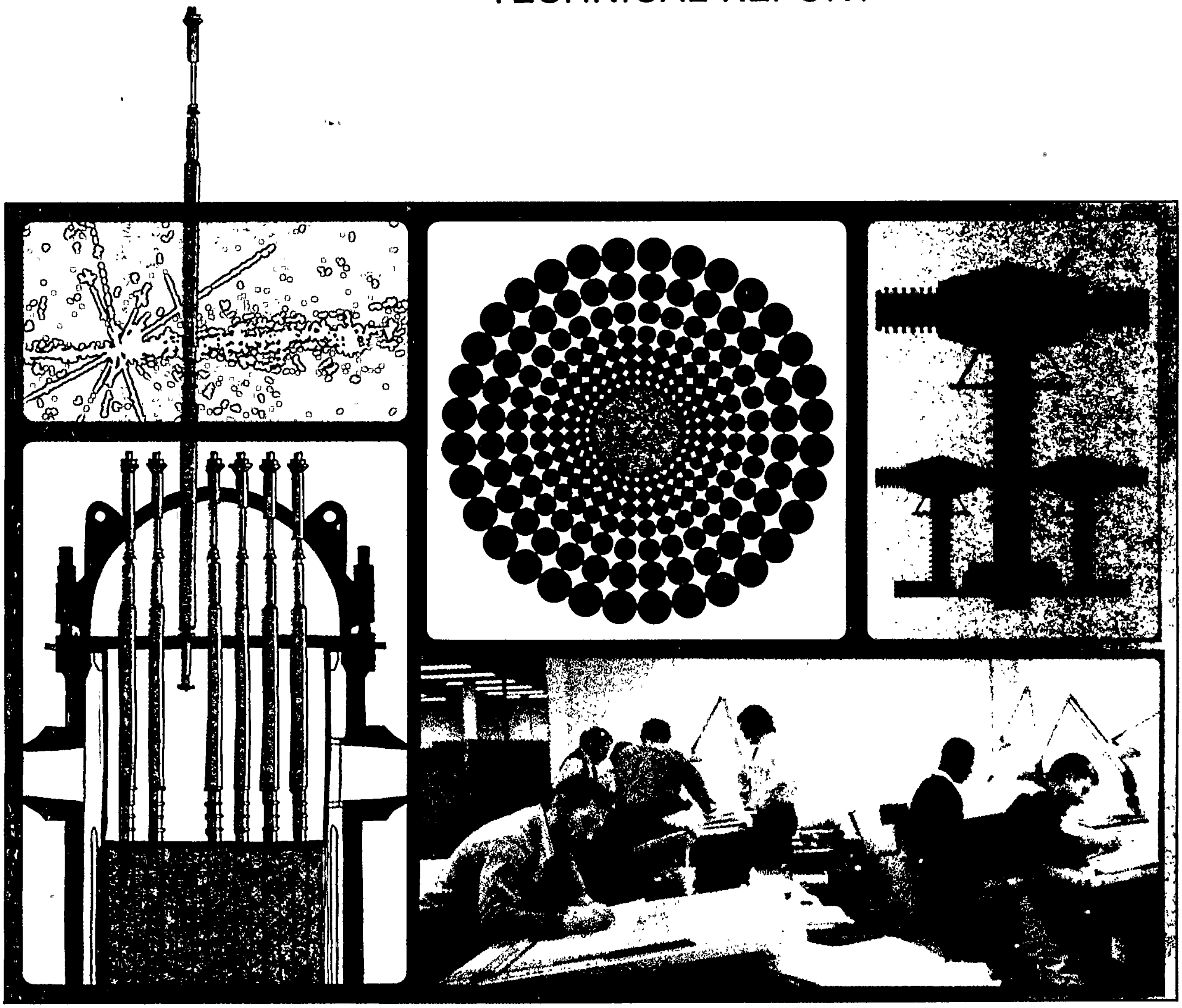
Chugging Loads — Revised Definition and Application Methodology for Mark II Containments (Based on 4TCO Test Results)

TECHNICAL REPORT



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Summary

Tests were conducted during 1975/76 by General Electric Company (GE) in their 4T test facility for the domestic Mark II utilities for the purpose of evaluating the containment pool dynamic effects resulting from a postulated loss-of-coolant accident (LOCA). Based on chugging data recorded during these tests, an empirical load definition was developed. This load definition was based on direct application of pressure traces measured on the boundary of the 4T test facility to the wetted perimeter of Mark II containments and, as a result, could not account for differences between the 4T test facility and the Mark II containments with respect to vent length (vent acoustics), suppression pool geometry (pool acoustics) and flexibility of suppression pool structural boundaries. In order to account for these differences, it became necessary to develop a chugging load definition at the "source" (i.e., at vent exit).

Such an improved chugging load definition was developed together with the application methodology for Mark II containments for specific application to Washington Public Power Supply System - Nuclear Project No. 2 (WNP-2). This definition was based on conclusions reached after evaluation of tests conducted to assess effects of steam-condensation phenomena in Mark II type (over/under) pressure suppression systems. Two main conclusions from these tests were:

a) chugging effects are mainly due to the sudden (impulsive) collapse of the steam-water interface which occurs near the vent exit during the chugging regime and, in view of this, chugging could be represented by an impulsive load applied there; and,

b) bulk fluid motions during chugging being relatively small, a linear formulation (small displacements/velocities) is adequate for predicting the dynamic pressures induced in the far field (away from vent exit) and the dynamic response of the pool boundary structures.

A single vent design load specification was derived to bound, statistically, the 4T test data supplied by GE as representative of Mark II conditions during LOCA. The application methodology for WNP-2 containment was also developed, properly accounting for all important plant specific parameters: length of downcomer vents (vent acoustics), 3-D multi-vent suppression pool geometry with a sloped bottom (pool acoustics) and the flexibility of the suppression pool structural boundary.

Two loading conditions were developed for, and considered in the design of, the multi-vent configuration of WNP-2: a nearly symmetrical loading and an asymmetric loading.

Additional condensation tests were performed during 1979-1980 by GE for the U.S. Mark II Owners Group, in a modified configuration of the 4T test facility, known as the "4TCO" test facility. Selected and conservatively representative (most severe) 4TCO chugging data supplied by GE were evaluated/analyzed with the objectives:

a) to examine in light of the 4TCO data, the adequacy of the existing improved chugging load definition; and,

b) to revise, where necessary, this (improved) load definition and the application methodology for the Mark II containment of WNP-2.

Analysis of the 4TCO chugging data, as well as of the chugging data which became available from other tests during the same time period, resulted in the following main findings:

a) the impulsive nature of chugging (sudden collapse of the steam-water interface) was confirmed;

b) it was determined that the 4TCO data included some stronger/larger amplitude chugs which exhibited characteristics (frequency content, spatial distribution) different from those of the 4T chugs;

c) the random nature of chugging was confirmed;

d) the strength/amplitude of chugging, although random, appeared to be dependent on system conditions, i.e., stronger chugs appeared to cluster within limited time windows corresponding to specific system conditions.

As a consequence, the following revisions to the single vent design load specification were implemented:

- the "source" load was defined as an impulsive pressure gradient (acceleration) applied over the steam-water interface at vent exit; this resulted in better matching of the characteristics exhibited by the stronger 4TCO chugs;

- to account for the random nature of the chug strength/amplitude each strongest ("key") chug was averaged (in terms of Fourier amplitude spectrum) with the largest neighboring ("companion") chug to obtain an "average" or "mean" chug for each time window for which 4TCO chugging data were supplied.

It is significant to note that the single vent design "source" load developed for WNP-2 in fact envelopes the 4TCO data at almost all locations of the 4TCO tank wetted boundary and throughout the frequency range of interest; it also envelopes the 4T data.

The two loading conditions originally developed for WNP-2 were basically retained (a nearly symmetrical loading and an asymmetric loading) in a manner compatible with the revised single vent design load specification. In order to account for physical realities observed during steam-condensation tests in multi-vent configurations (JAERI, CREARE), vent-desynchronization is specified for both these loading conditions adopting the approach used in the Long Term Improved Generic Chugging Load Definition developed by GE for Mark II Owners Group, in a manner compatible with the two loading conditions for WNP-2.

To verify the adequacy of chug strength averaging and of vent desynchronization, the dynamic pressures calculated on the wetted wetwell wall of WNP-2 were compared with wall pressures recorded during large-amplitude chugs in the 7-vent full scale tests conducted by the Japan Atomic Energy Research Institute (JAERI) in a test facility representative of the Mark II geometry. The calculated pressures were found to bound the JAERI data.

1.0 Introduction and Background

The original chugging load definition was developed using chugging data recorded during the 4T tests conducted by General Electric Company (GE) for the domestic Mark II utilities in the 4T (single vent/unit cell) test facility during late 1975 and early 1976, [1]. This load definition was based on direct application of pressure traces measured on the boundary of the 4T test facility to the wetted perimeter of Mark II containments, [2]. It soon became apparent that this method of application of 4T data to Mark II containments did not account for differences between the 4T test facility and the Mark II containments with respect to vent length (vent acoustics), single vent versus multi-vent suppression pool geometry and flexibility of suppression pool structural boundaries. In order to account for these differences, it became necessary to develop a chugging load definition at the "source", i.e., at vent exits.

Because of schedule constraints, such an improved chugging load definition was developed, together with the application methodology to Mark II containments, for specific application to Washington Public Power Supply System - Nuclear Project No. 2 (WNP-2) during 1978/79, [3, 4]. A single vent design load specification was derived to bound, statistically, the 4T test data supplied as being representative of Mark II containment conditions expected during a postulated LOCA.

The single vent design load was defined as a pressure source at the vent exit and since its definition was independent of the 4T test facility characteristics which were different from those of WNP-2 (vent length, suppression pool geometry and flexibility of suppression pool structural boundary) it was assumed to be directly transferable to vent exits in the WNP-2 containment. Two loading conditions were developed and considered in the design of WNP-2: a nearly symmetrical loading and an asymmetric loading. The application methodology for WNP-2 containment accounted for the plant specific parameters governing the response: length of downcomer vents, 3-D multi-vent suppression pool geometry with a sloped bottom, and the flexibility of suppression pool structural boundary (steel containment, the concrete pedestal and the foundation mat).

In 1979-1980, additional condensation tests were performed by GE for the U.S. Mark II Owners Group in a modified configuration of the 4T test facility, known as the "4TCO" test facility [5]. The original 4T test facility included a drywell located adjacent to the wetwell, a configuration which required a vent with three bends and a total length of about 90 feet. In the 4TCO facility, the drywell vessel was mounted

above the wetwell to represent the over/under pressure suppression configuration with straight vertical vent, approximately 45' long, representative of Mark II plants. Although the 4TCO tests were planned and performed with the objective of gathering test data to be used for confirmation of the DFFR Condensation Oscillation (C.O.) load definition, the data were recorded for the entire transient including chugging, thus providing an additional data base for chugging as well.

Selected chugging data obtained from regions of the 4TCO tests during which the most severe chugging effects were recorded were made available by General Electric Company as being conservatively representative for Mark II plants during the chugging regime. The 4TCO chugging data supplied, [6], are evaluated and results and conclusions presented in this report. The conclusions of this evaluation together with the conclusions reached following the evaluation of multi-vent test data by GE and presented in Reference 7 report (regarding the random nature of chug strength and chug initiation time from vent-to-vent during a pool chug in a multi-vent configuration) are used in this report:

(a) to examine in light of the 4TCO data, the adequacy of the (improved) chugging load definition developed previously, using 4T data, for application to WNP-2 [3, 4], and

(b) to revise, where necessary, this (improved) chugging load definition and the application methodology for the Mark II containment of WNP-2.

The 4TCO chugging data supplied by General Electric and the multi-vent tests evaluated by General Electric are identified in Chapter 2.

The evaluation of 4TCO chugging data including the analytical studies performed in the process of data evaluation and the characteristics of single vent 4TCO chugs derived from data evaluation/analysis are described in Chapter 3. The evaluation shows that revision in the improved chugging load definition is necessary.

The revised single vent load definition and the revised application methodology for the Mark II containment of WNP-2 based on the conclusions reached following the evaluation of 4TCO test data (presented in Chapter 3) and on the conclusions reached from the evaluation of multi-vent test data (presented by General Electric in Reference 7) are presented in Chapter 4.

The results of application of the revised chugging load definition to the WNP-2 plant (i.e., reactor building/containment structure responses) are presented in Chapter 5.

2.0 The New Chugging Data

2.1 The Single Vent 4TCO Test Data

The 4TCO test facility, test variables, test matrix, test instrumentation and test results are described in detail in Reference 5. The test facility is shown in Figure 2-1. The wetwell pressure transducer locations are shown in Figure 2-2.

The pressure time histories recorded at the bottom center (channel 28) were scanned by General Electric Company to identify significant chugs. Two hundred ninety-seven chugs were identified (See Table 4-2 of Reference 7).* Table 2-1 provides a summary of the 4TCO chug data compiled from information provided by General Electric [8] in November 1980.

Table 2-1 identifies seven regions from six tests which recorded the largest chugs (based on the bottom center pressure (BCP) mean square power (msp) and peak over pressure

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*Information from Reference 8 is provided in Tables 2-1 and 2-2 of this report for identification of chug numbers and time window numbers used in this report and to establish their correspondence with information subsequently published in Reference 7.

(POP)) of all 4TCO tests. General Electric Company selected 7 key chugs (one for each of the seven regions) because the power spectral density (PSD) envelope of these chugs closely approximated the PSD envelope of the entire sample of chugs [7, 8]. Several chugs (called neighboring chugs) occurring before or after each of the seven key chugs together with the key chug define a region, or a time window making seven regions [8]. The region numbers and the number of chugs in each region are also identified in Table 2-1. A total of 35 chugs in seven regions or time windows were selected by General Electric Company as the chugging data base [8]. The 4TCO chugging data base identification parameters are shown in Table 2-2.

The 4TCO bottom center pressure time histories for the thirty-five chugs were recorded on magnetic tapes at .4939 millisecond interval and supplied to Burns and Roe [9]. In addition, the data from all the 28 replay channels from all tests were digitized at 1 millisecond interval and supplied on magnetic tapes to the Mark II Owners Group [6]. The data for the 35 chugs of the chugging data base were obtained from these tapes for the evaluation presented in Chapter 3.

2.2 Multi-vent Test Data

Multi-vent test data from two test programs (the CREARE subscale tests and the JAERI full scale tests) have

recently become available. General Electric Company has evaluated these multi-vent test data for the Mark II Owners Group and has incorporated the significant findings of multi-vent effects (the random nature of chug strength and chug initiation time from vent-to-vent during a pool chug in a multi-vent configuration) in the Generic Chugging Load Definition Report [7]. The results of these data evaluations and conclusions reached will also be adopted for the chugging load definition for WNP-2.

3.0 4TCO Chugging Data Evaluation and Analytical Studies

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CHUGGING LOADS - REVISED DEFINITION AND

APPLICATION METHODOLOGY FOR MARK II CONTAINMENTS

(based on 4TCO test results)

TECHNICAL REPORT

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BURNS AND ROE, INC.

for application to

WASHINGTON PUBLIC POWER SUPPLY SYSTEM

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4.6.1 Computational Methodologies

'WNP-2' Methodology

The computation methodology used for the source extraction from the 4TCO data and for its application to the multi-vent WNP-2 containment are similar to those used in Reference 3. Namely, a fully coupled model representing the vent steam/suppression pool water/4TCO tank structure was used for source extraction, thus resulting in an impulsive source free of the test facility characteristics. Similarly, the computational methodology for application of the "source"

design load to the multi-vent geometry of WNP-2 containment utilized a fully coupled model which directly accounted for all important plant specific parameters: length of downcomer vents (vent acoustics), 3-D multi-vent suppression pool geometry with a sloped bottom (pool acoustics) and the flexibility of the suppression pool structural boundaries.

Generic Methodology

Subsequent to the development of the above methodology [3], General Electric Company presented an improved chugging methodology [18] and more recently the generic chugging load definition based on the 4TCO and multi-vent test data [7]. The methodology developed by GE [18,7] is based on principles which are similar to those of the WNP-2 methodology. It recognizes the impulsive nature of chugging, acoustic nature of the steam response in the vent, acoustic nature of the water response in the pool, and it recognizes the need to address in the load definition the presence of vent response characteritics and of the fluid-structure interaction (FSI) effects in the dynamic pressures measured in the test facility. However, the computational methodologies used for source extraction from test data and for its application to the multi-vent Mark II containments are based on two assumptions [18] (not required in the 'WNP-2' computation methodology):

(a) The vent is not acoustically coupled to the pool, and

(b) The principal effect of the fluid-structure interaction (FSI) is to reduce the frequency of the tank ringout.

With the above two assumptions, the hydrodynamic model of the test facility used for source definition is reduced to solving an acoustic wave equation in a flat bottom axisymmetric rigid tank. To account for the vent participation, vent harmonic (sine wave) response is added as a forcing function to the impulsive pressure source.

Prior to application of these sources to Mark II plants two modifications are required to account for the differences, if any, in the vent response characteristics and in the FSI response characteristics between the test facility and the Mark II plant as described in References 7 and 18.

The hydrodynamic model of the Mark II containment used in calculating the chugging boundary pressures due to a source consists of solution of the acoustic wave equation in a rigid, flat bottom annular tank.

4.6.2 WNP-2 Plant Unique Characteristics

There are two characteristics of the WNP-2 plant which are not in common with the other domestic Mark II plants:

- containment shell structure built of stiffened steel plate,
- the sloped bottom pool geometry.

The evaluation of the 4TCO data presented in Chapter 3 shows that the boundary pressure traces from key chugs contain significant participation of the FSI response. The magnitude of its participation vary from chug to chug and is dependent on the system conditions. Since the WNP-2 containment shell structure is built of steel (as is the 4TCO tank wall), its response to impulsive chugging sources will include significant participation of the FSI mode (as in the 4TCO tank) which may be axisymmetric as well as non-axisymmetric. To obtain realistic responses of the WNP-2 containment to chugging loads, it is essential to use the methodology which directly accounts for the FSI effects of the test facility in the source extraction methodology (thus resulting in sources which are free of the test facility characteristics) and which directly accounts for the FSI effects (axisymmetric as well as non-axisymmetric) in the containment response calculations.

As stated before, the generic methodology is applicable to a containment with a flat bottom pool geometry. Its use for WNP-2 containment would require idealization of the sloped bottom floor to a flat bottom floor. Such an idealization could be practically based on only one (the fundamental) pool acoustics mode. Since the Mark II pool acoustic response to chugging loads involves participation of many modes of vibrations of the coupled vent/pool/structure system, such an idealization would result in over-simplification of the problem.

For the above reasons, the 'WNP-2' revised chugging load definition is developed, implemented and presented in this report.

4.6.3 Application Methodologies for Mark II Containments

Elements of the two load application methodologies for Mark II containments are similar.

Based on multi-vent test data both methodologies:

- recognize random variation of chug strength from vent-to-vent and use an averaging technique (although averaging is used in 'WNP-2' definition, it is shown that design sources bound all unaveraged 4TCO data at Channel 28),

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- recognize random variation of chug initiation times from vent-to-vent (the 'WNP-2' methodology conservatively assumes that the three vents in one radial row are in-phase, see Chapter 5).

5.0 WNP-2 Reactor Building Resonse To Chugging Load

5.1 Introduction

The application of the chugging load methodology of the previous chapters is presented in this chapter. The theoretical background of the structural analysis is presented. The structural and suppression pool models are discussed. The results of the analysis, and their comparison with JAERI test results are presented.

5.2 Theoretical Background

The analytical methods that were used in the application of this chugging load methodology to the WNP-2 containment is similar to that of Reference 3, Section 5.1. It was shown that the total hydrodynamic pressures, $\underset{\sim}{P}_2(\Omega)$ on the fluid-structure boundary can be expressed by

$$\underset{\sim}{P}_2(\Omega) = \underset{\sim}{P}_i(\Omega) + \underset{\sim}{M}_a(\Omega)\,\ddot{\underset{\sim}{U}}(\Omega) \qquad (5.1)$$

where

$\underset{\sim}{P}_i(\Omega)$ = Rigid wall pressures

$\underset{\sim}{M}_a(\Omega)$ = Hydrodynamic added mass matrix

Ω = Forcing frequency

$\ddot{\underset{\sim}{U}}(\Omega)$ = Accelerations of the fluid-structure interface

The structural equation of motion can then be expressed as

$$\underset{\sim}{K}(\Omega)\ \underset{\sim}{U_S}(\Omega) = -\underset{\sim}{T}\ \underset{\sim}{P_i}(\Omega) \qquad (5.2)$$

where

$\underset{\sim}{U_S}(\Omega)$ = Structural displacements

$\underset{\sim}{T}$ = Appropriate transformation matrix

$\underset{\sim}{K}(\Omega)$ = Dynamic stiffness matrix

$$= -\Omega^2 (\underset{\sim}{M_S} + \underset{\sim}{T}\ \underset{\sim}{M_a}\ \underset{\sim}{T^T}) + i\Omega\ \underset{\sim}{C_S} + \underset{\sim}{K_S} \qquad (5.3)$$

$\underset{\sim}{M_S}$ = Structural mass matrix

$\underset{\sim}{C_S}$ = Structural damping matrix

$\underset{\sim}{K_S}$ = Structural stiffness matrix

i = $\sqrt{-1}$

For any specified case of loading, the rigid wall pressures $\underset{\sim}{P_i}(\Omega)$ can be obtained, equation 5.2 can then be solved to obtain the required structural displacements. For more details, refer to Reference 3.

5.2.1 Treatment of Multiple Vents

A cross sectional view of the WNP-2 reactor building is shown in Figure 5-1 and a plan view of the wetwell at the

elevation of vent exits is shown in Figure 5-2. There are 102 downcomers (18 downcomers of 28" diameter and 84 downcomers of 24" diameter) located in thirty-four radial lines arranged in an axisymmetric manner.

A three dimensional finite element model of the WNP-2 suppression pool that has a set of three vents in one radial row is shown in Figure 5-3 and its structural boundary in Figure 5-4. The analysis is performed for any given chugging loading case using this model and assuming the source loads at the three vent exits to be of a unit strength and occurring in-phase. The structural and pool responses are evaluated then for this set of three vents. Let the response measure of interest located at angle θ and time t from the reference radial vent row be represented by the vector X (θ,t). If the chugging load intensity at the vent exits corresponding to the i^{th} radial row is assumed to be L_i, the total building response, U (θ,t), can be obtained as:

$$\underset{\sim}{U}(\theta,t) = \sum_{i=1}^{34} L_i \cdot \underset{\sim}{X}(\theta-\theta_i, t-\tau_i) \qquad (5.4)$$

where

θ_i = The angular position of the i^{th} radial row measured from the reference row as shown in Figure 5-2.

τ_i = Random chug start time for the i^{th} radial row, Table 5-1.

The assumption that the chugs occur in-phase at the three vents in each row is more conservative than the case where all 102 vents are assumed desynchronized since the variance of the chug start times assigned to 34 radial rows is smaller than the variance of the chug start times assigned to 102 vents.

5.3 WNP-2 Response to Chugging Loads

The single vent load definition and the associated multi-vent application methodology of Chapter 4 and the theoretical approaches of Section 5.2 are used to obtain the suppression pool boundary pressures and structural responses to chugging loads. The axisymmetric finite element model of the reactor building is shown in Figure 5-5. This model is a more refined version of the model used in Reference 3. It was shown that refined modeling techniques give more realistic results (Reference 11).

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5.3.1 Containment Wall Design Pressures and Comparison With Test Data

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To obtain the maximum pool boundary pressures for comparison with test data, the source strengths at the WNP-2 vents were assumed equal and the sources along the 34 radial rows were assumed desynchronized with chug start times as given in Table 5-1. The maximum rigid wall pressure value calculated at the containment wall at the vent exit elevation at 0° azimuth for each design source is shown in Table 5-2.

The maximum rigid wall pressure measured at the vent exit elevation in the 4TCO system (Channel 20) during each of the seven time-windows (Table 2-2) and its average with maximum pressure of the companion chug (Table 4.1) is shown in Table 5-3.

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The maximum modified* pressures measured in different JAERI tests at the vent exit elevation at the containment wall are shown in Table 5-4. Its comparison with the design wall pressures of Table 5-2 shows that the design wall pressures are higher than the JAERI results.

To provide additional comparison with JAERI data, Fourier amplitude spectrum of the containment wall pressures at the vent exit elevation at 0° azimuth was obtained for each of the seven design sources. The envelope of the seven spectra is shown in Figure 5-6 and compared with the envelope of Fourier amplitude (modified averaged) spectra of measured pressures in JAERI tests [7]. The envelope of design pressures completely envelopes the JAERI data by a significant margin at all frequencies.

The above comparisons demonstrate that the chugging load definition including the averaging method and the desynchronization procedure used in the application methodology for the Mark II containments is conservative.

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* The JAERI multi-vent test facility shown in Figure 3-1 of Reference 7 includes 7 vents in a 20° sector. The WNP-2 vent configuration shown in Figure 5-2 shows six vents in a 21.8° sector. In order to account for this difference in the number of vents between the two systems, JAERI test results are divided by a factor of 1.17 based on a previous study [19], which compared peak boundary pressures resulting from in-phase equal strength source application to seven vents versus six vents in a 20° segment.

5.3.2 Structural Response

Structural responses were calculated using the axisymmetric finite element model of the reactor building shown in Figure 5-5 subjected to the pool boundary pressures calculated for each of the seven design sources. Response spectra at several locations were calculated. The envelope spectrum curves (with the peaks spread by ±15%) corresponding to 0.5%, 1%, 2% and 4% of the critical damping values are plotted for selected locations (foundation mat at primary containment vessel, RPV pedestal at vessel support elevations, containment vessel at stabilizer truss level, containment vessel at mid-submergence depth and reactor building at elevation 521') in Figures 5-7 and 5-8 for the asymmetric and the nearly symmetric loading cases, respectively.

5.4 Discussion of the Calculated Structural Response to Chugging Loads

The calculated WNP-2 reactor building responses to chugging loads show a pattern similar to that of the calculated responses to SRV loads, Reference 11. The reactor building can be divided again into three zones:

i. The wetwell zone, including the containment structure boundary, where the hydrodynamic pressures are applied, and where the structural responses are the largest.

ii. The drywell zone, including the containment structure boundary, where the high responses of zone (i) have been attenuated through the RPV pedestal and the containment shell. Although smaller, they are still of a finite magnitude for the low damped steel containment structure.

iii. The third zone consists of the biological shield and the reactor building walls and floors outside primary containment. The structural response accelerations calculated for WNP-2 are negligibly small. It is noted here that negligibly small responses were also calculated for WNP-2 when subjected to SRV loads [11] and this low level of predicted response was verified by measurements taken during Caorso and Tokai-2 SRV tests. This is due to the fact that the load path from zone (i) where the hydrodynamic pressures are applied, to this zone is through the mat and the soil and as shown in References 12 and 13 the soil compliances reduce rapidly as the frequency of excitation increases; this explains the above mentioned large reductions in the structural responses in this zone.

Table 5-5 shows the maximum computed structural response accelerations in the three zones of the WNP-2 reactor

building. Figure 5-9 shows the vibration tolerance observations as documented in References 14, 15 and 16. Examination of the maximum computed structural response accelerations at locations outside the containment structure of WNP-2 reactor building (zone iii) indicates that they fall consistently near the curve of Figure 5-9 labeled "BEGIN TO PERCEIVE". These findings lead to the conclusion that evaluation of safety related piping and equipment for chugging responses need only be carried out in zones (i) and (ii). It is noted that this conclusion is consistent with the results of WNP-2 reactor building analysis for SRV loads (Reference 11).

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8. "4T C.O. Chugging Data Base Information," General Electric Company Letter MKII-1970-E (including seven Attachment), dated November 18, 1980 to Burns and Roe, Inc.

9. Letter dated July 24, 1980 from Creare Inc. to Burns and Roe, Inc.

10. "Random Data: Analysis and Measurement Procedures," J. S. Bendat, A. G. Piersol, Wiley-Interscience, 1971.

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12. "Dynamic Response of Structures in Layered Soils," V. Chang-Liang, Department of Civil Engineering Report Number R74-10, Massachusetts, 1974.

13. "Dynamic Stiffness Functions of Strip and Rectangular Footings on Layered Media," G. Gazetas, Massachusetts Institute of Technology, Dept. of Civil Engineering, M.S. Thesis, 1975.

14. "Data Averaged From 7 Sources," Report 1, D. E. Goldman, Naval Medical Research Institute, March 1948.

15. "Foundation Vibrations," R. E. Richart, Journal of ASCE, Vol. 86, No. SM-4, August 1960.

16. "Vibration of Isolated Foundations for Boiler Feedpumps," H. A. Franklin, Presented at the 1979 Annual Convention, American Concrete Institute, Milwaukee, Wisconsin, March 1979.

17. "Improved Structural Analysis Methods For Prediction of Containment - Response to Suppression Pool Hydrodynamic Loads", Technical Report, Revision 2, Prepared by Burns and Roe, Inc. for General Electric Company, January 1981.

18. "Mark II Improved Chugging Methodology", General Electric Document NEDE 24822 (Proprietary), May 1980.

19. "Fukushima Dai-Ni: Unit 3, Containment Response to the LOCA Steam Condensation Loads" Technical Report (Proprietary), prepared by Burns and Roe, Inc., for Toshiba Corporation April 1981.

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TABLE 2-1

SUMMARY OF 4TCO CHUG DATA

Table 2-2

4TCO CHUGGING DATA BASE IDENTIFICATION PARAMETERS

TABLE 4-1

IDENTIFICATION OF THE COMPANION
CHUG USED FOR AVERAGING WITH KEY CHUG

TABLE 4-2

SINGLE VENT DESIGN
SOURCE DEFINITION

TABLE 5-1

CHUG START TIMES FOR RANDOM PHASING

Radial Row	Chug Start Time (Sec)	Radial Row	Chug Start Time (Sec)
1	0.022826	18	0.012603
2	0.021631	19	0.035364
3	0.014281	20	0.026404
4	0.037928	21	0.039039
5	0.026944	22	0.021682
6	0.025257	23	0.024879
7	0.0092329	24	0.044889
8	0.035325	25	0.024589
9	0.036614	26	0.0057321
10	0.017459	27	0.023880
11	0.030120	28	0.033905
12	0.018409	29	0.015641
13	0.034114	30	0.013154
14	0.041211	31	0.022173
15	0.034711	32	0.026808
16	0.024805	33	0.046634
17	0.031562	34	0.027705

Variance = 0.981708×10^{-4} (sec.)^2

Note: The three vents in each radial row are assumed to chug in-phase.

TABLE 5-2

MAXIMUM RIGID WALL PRESSURES ON WNP-2
CONTAINMENT AT VENT EXIT ELEVATION (NODE 15)

TABLE 5-3

4TCO PRESSURE MAXIMUMS AND AVERAGE
AT CHANNEL 20

BURNS AND ROE, INC. PROPRIETARY
GENERAL ELECTRIC COMPANY PROPRIETARY

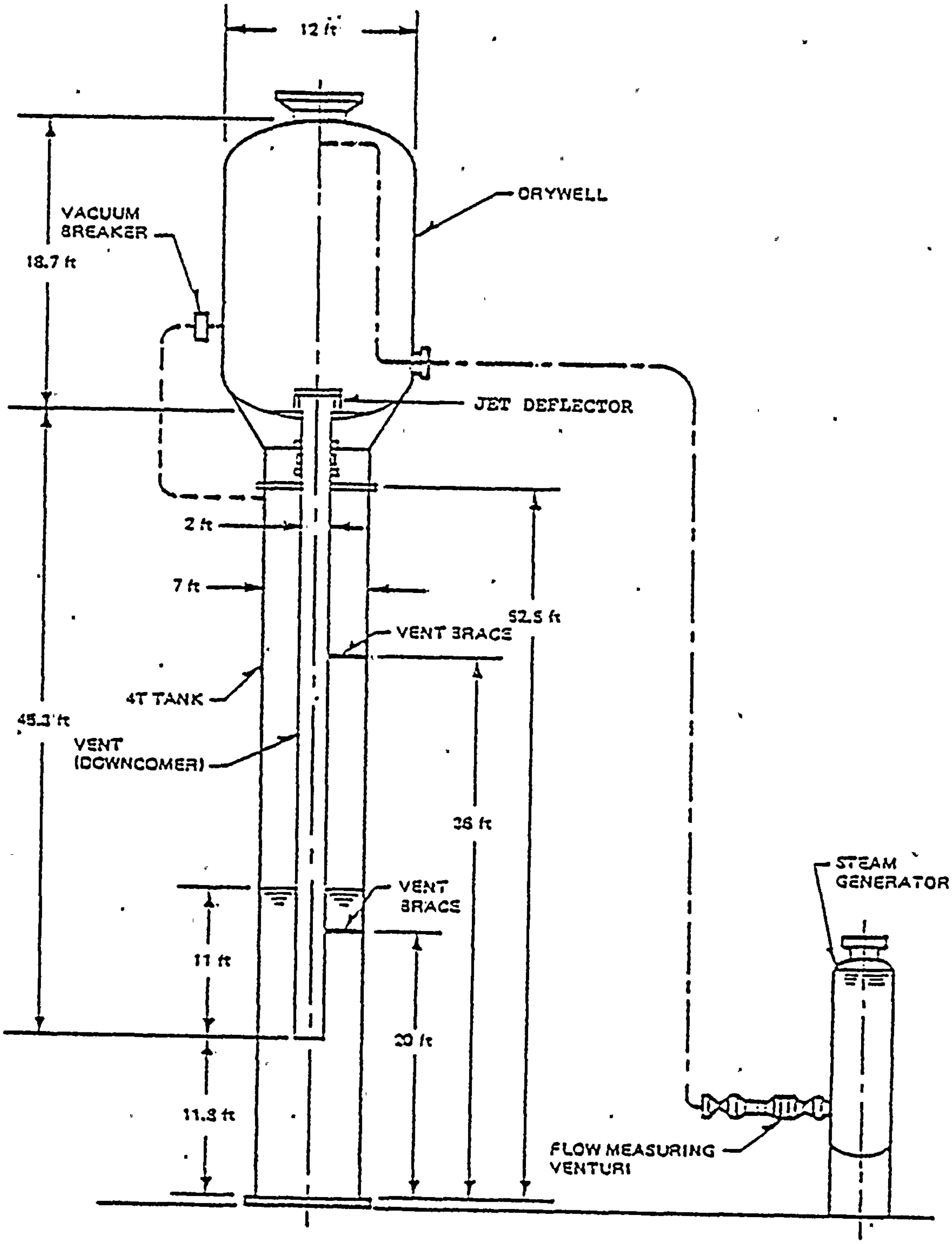
TABLE 5-4

JAERI PEAK POSITIVE CHUGGING
PRESSURE AMPLITUDES

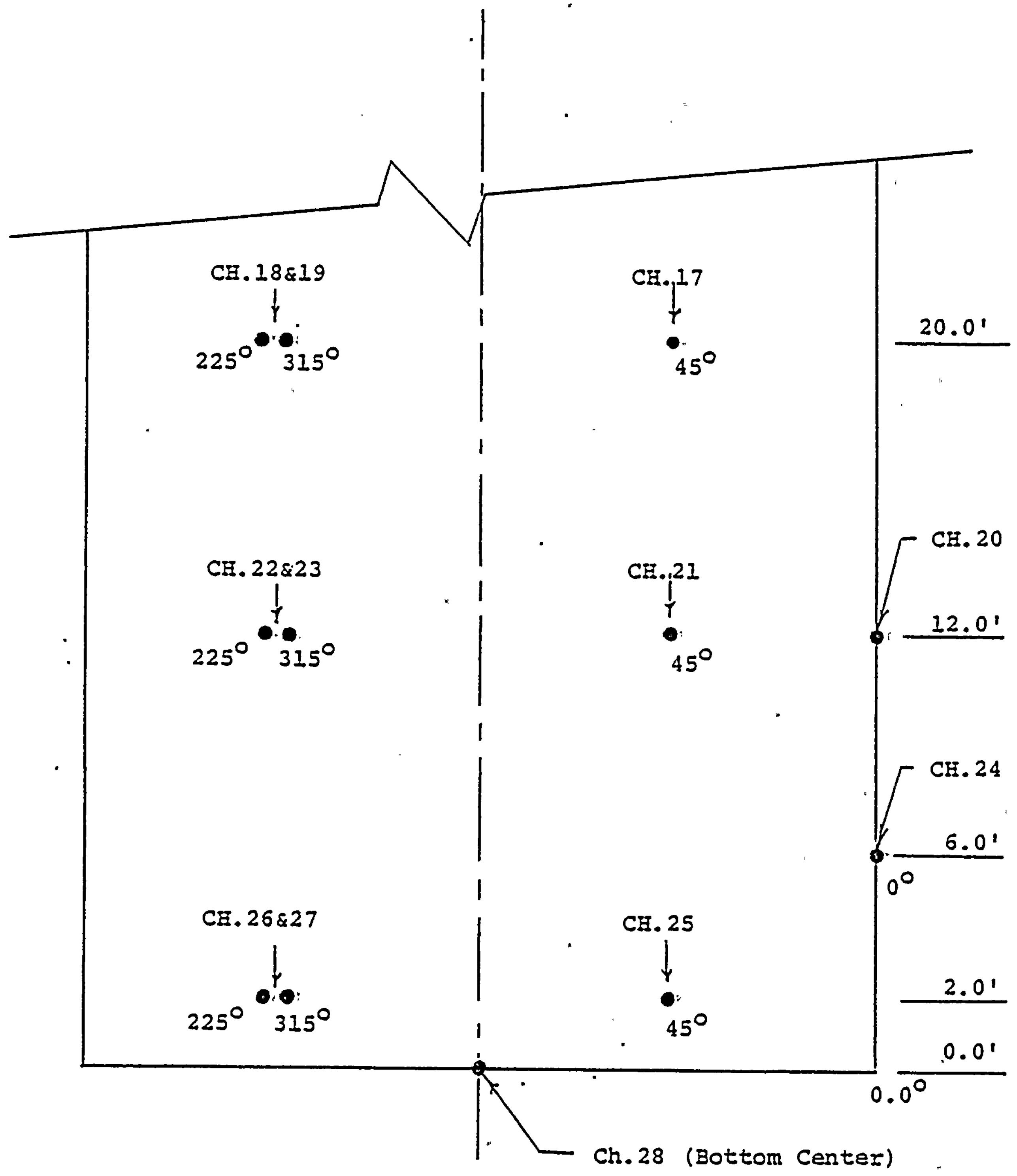
TABLE 5-5

MAXIMUM COMPUTED ACCELERATIONS FOR
WNP-2 REACTOR BUILDING

ZONE	LOCATION	RESPONSE DIRECTION	MAXIMUM ACCELERATION (g)
I Inside and on the boundary of the containment structure below El. 510'	Containment Wall (Quencher Elevation)	Horizontal	1.63
II Inside and on the boundary of the containment structure above El. 510'	Containment Wall El. 520'	Horizontal	0.18
	RPV Support	Vertical	0.060
	Stabilizer Truss	Horizontal	0.038
III Outside the containment structure	Outside Building Wall El. 521'	Horizontal	0.002
		Vertical	0.029



WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	Test Configuration for Mark II Condensation Oscillation (4TCO) Tests	FIGURE 2-1



WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	4TCO Tests Wetwell Pressure Transducer Locations	FIGURE 2-2

GENERAL ELECTRIC COMPANY PROPRIETARY

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	COMPARISON OF PRESSURES & FOURIER AMPLITUDE SPECTRA OF KEY CHUG & A NEIGHBORING CHUG - TIME WINDOW NO. 1	FIGURE 3-1

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	COMPARISON OF PRESSURES & FOURIER AMPLITUDE SPECTRA OF KEY CHUG & A NEIGHBORING CHUG - TIME WINDOW NO. 2	FIGURE 3-2

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	COMPARISON OF PRESSURES & FOURIER AMPLITUDE SPECTRA OF KEY CHUG & A NEIGHBORING CHUG - TIME WINDOW NO. 3	FIGURE 3-3

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	COMPARISON OF PRESSURES & FOURIER AMPLITUDE SPECTRA OF KEY CHUG & A NEIGHBORING CHUG - TIME WINDOW NO. 4	FIGURE 3-4

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	COMPARISON OF PRESSURES & FOURIER AMPLITUDE SPECTRA OF KEY CHUG & A NEIGHBORING CHUG - TIME WINDOW NO. 5	FIGURE 3-5

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	COMPARISON OF PRESSURES & FOURIER AMPLITUDE SPECTRA OF KEY CHUG & A NEIGHBORING CHUG - TIME WINDOW NO. 6	FIGURE 3-6

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	COMPARISON OF PRESSURES & FOURIER AMPLITUDE SPECTRA OF KEY CHUG & A NEIGHBORING CHUG - TIME WINDOW NO. 7	FIGURE 3-7

GENERAL ELECTRIC COMPANY PROPRIETARY

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	COMPARISON OF PRESSURES MEASURED AT CHANNEL 28 AND CHANNEL 26 DURING TIME WINDOW NO. 6 ,CHUG #2	FIGURE 3-8

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	COMPARISON OF PRESSURES MEASURED AT CHANNEL 24 AND CHANNEL 20 DURING TIME WINDOW NO. 6, CHUG #2	FIGURE 3-9

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	PHASE RELATIONSHIP BETWEEN PRESS. MEASURED AT CHANNEL 20 AND CHANNEL 28 VERSUS FREQUENCY-TIME WINDOW NO.1	FIGURE 3-10

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	PHASE RELATIONSHIP BETWEEN PRESS. MEASURED AT CHANNEL 20 AND CHANNEL 28 VERSUS FREQUENCY-TIME WINDOW NO.1	FIGURE 3-11

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	RATIOS OF FOURIER AMPLITUDES OF PRESSURES MEASURED AT CHANNEL 28/ CHANNEL 20	FIGURE 3-12

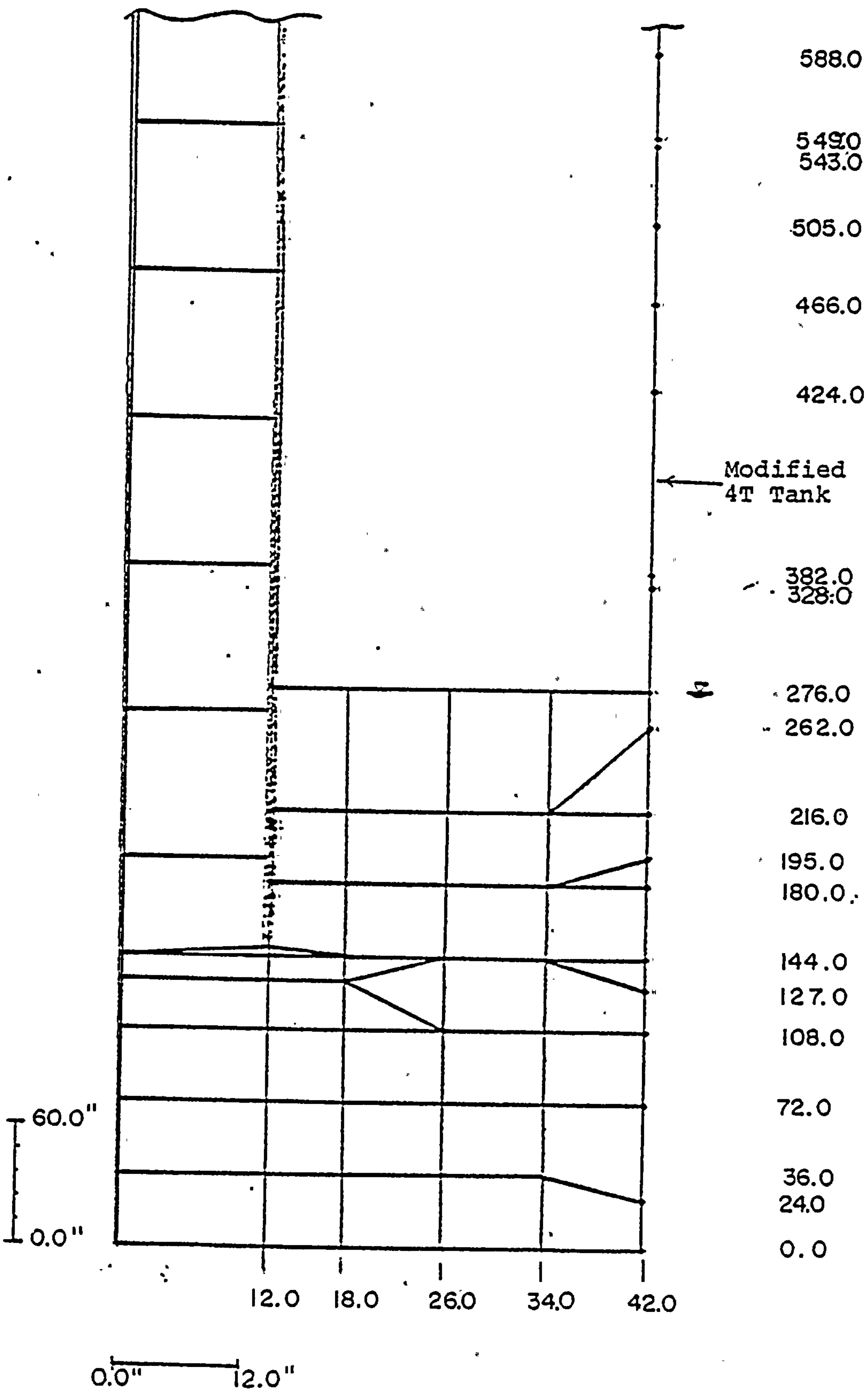
GENERAL ELECTRIC COMPANY PROPRIETARY

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	VERTICAL DISTRIBUTION OF PEAK PRESSURES-SIX CHUGS, TIME WINDOW No. 1	FIGURE 3-13

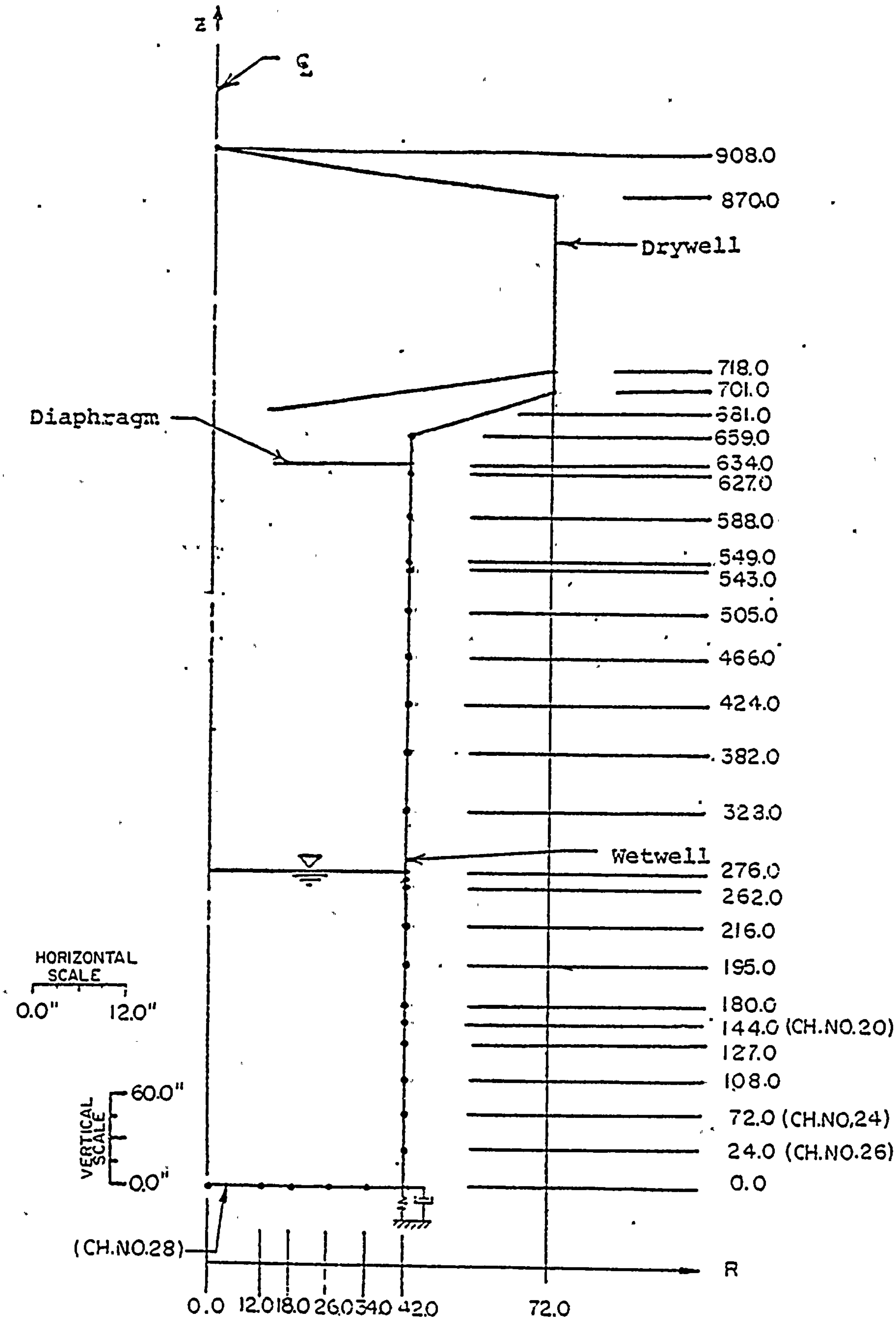
WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	VERTICAL DISTRIBUTION OF PEAK FOURIER AMPLITUDES OF PRESSURES TWO CHUGS-TIME WINDOW NO. 1	FIGURE 3-14

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	RATIO OF FOURIER AMPLITUDES OF PRESSURES MEASURED AT CH.20/CH.21	FIGURE 3-15

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	COMPARISON OF 4TCO & 4T DATA - PRESSURES MEASURED AT BOTTOM CENTER	FIGURE 3-16

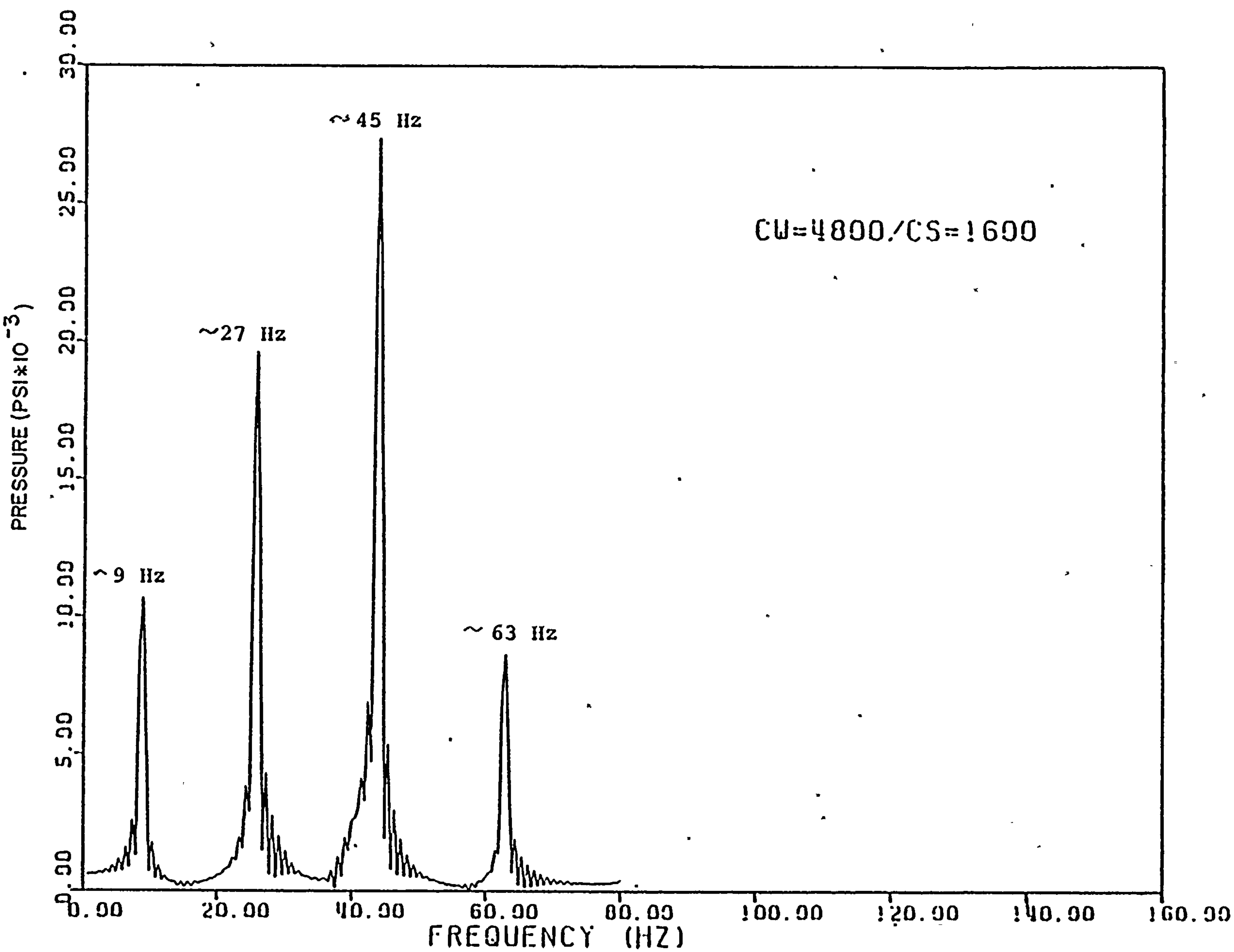


WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	VENT - POOL MODEL (FLUID ELEMENTS)	FIGURE 3-17a



WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	STRUCTURAL FINITE ELEMENT. MODEL OF 4TCO TANK	FIGURE 3-17b

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	SCHEMATIC PRESENTATION OF PRESSURE SOURCE AT VENT EXIT IN 4TCO SYSTEM	FIGURE 3-18



WASHINGTON PUBLIC POWER SUPPLY SYSTEM
NUCLEAR PROJECT NO. 2

FOURIER AMPLITUDE SPECTRUM OF PRESS. CALCULATED AT CH.28 WITH PRESSURE SOURCE AT VENT EXIT

FIGURE 3-19

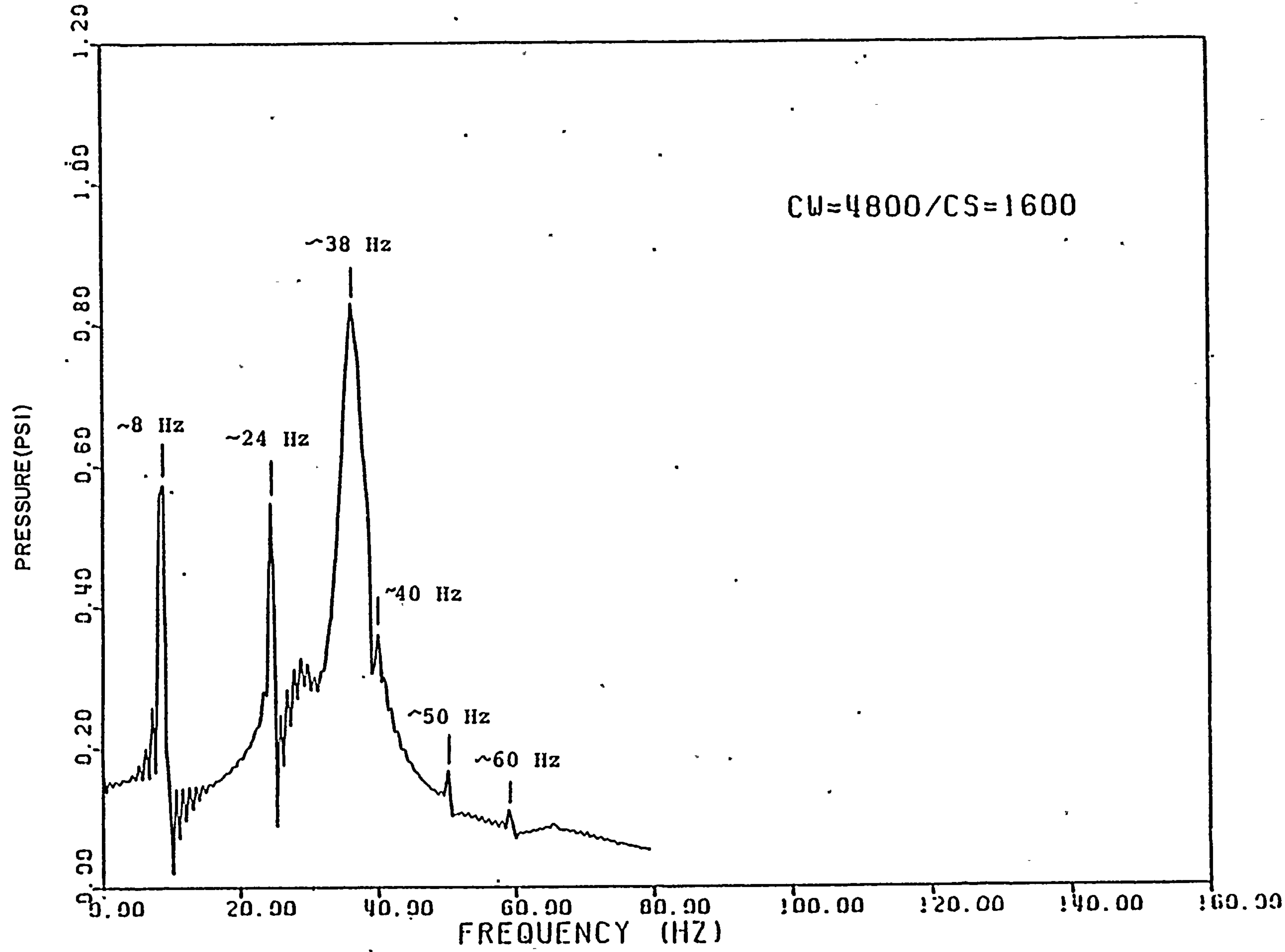
BURNS AND ROE, INC. PROPRIETARY

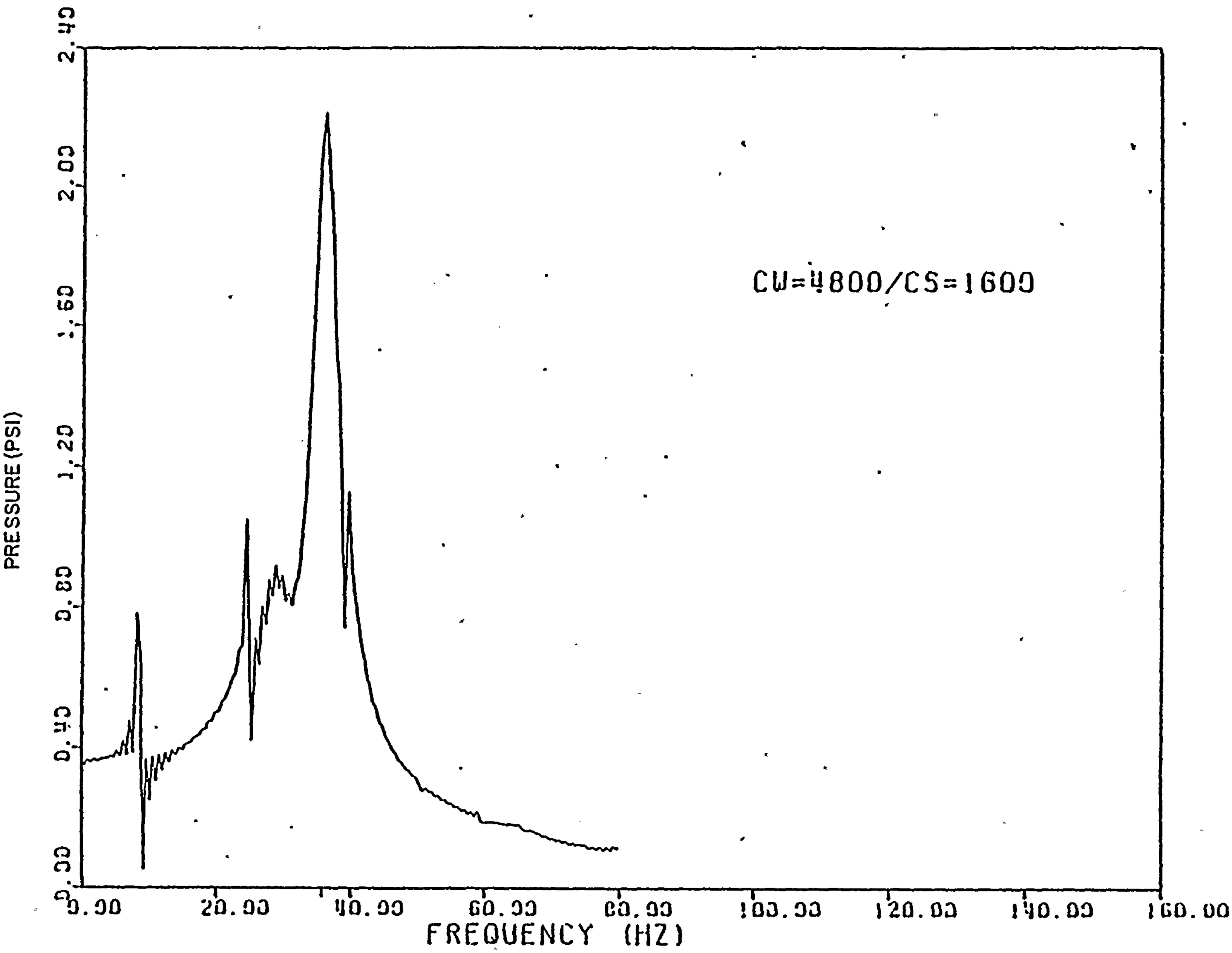
WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	SCHEMATIC PRESENTATION OF ACCELERATION SOURCE AT THREE LOCATIONS IN 4TCO SYSTEM	FIGURE 3-20

WASHINGTON PUBLIC POWER SUPPLY SYSTEM
NUCLEAR PROJECT NO. 2

FOURIER AMPLITUDE SPECTRUM OF PRESSURE CALCULATED AT CH.28 WITH ACCELERATION SOURCE AT VENT EXIT

FIGURE .3-21

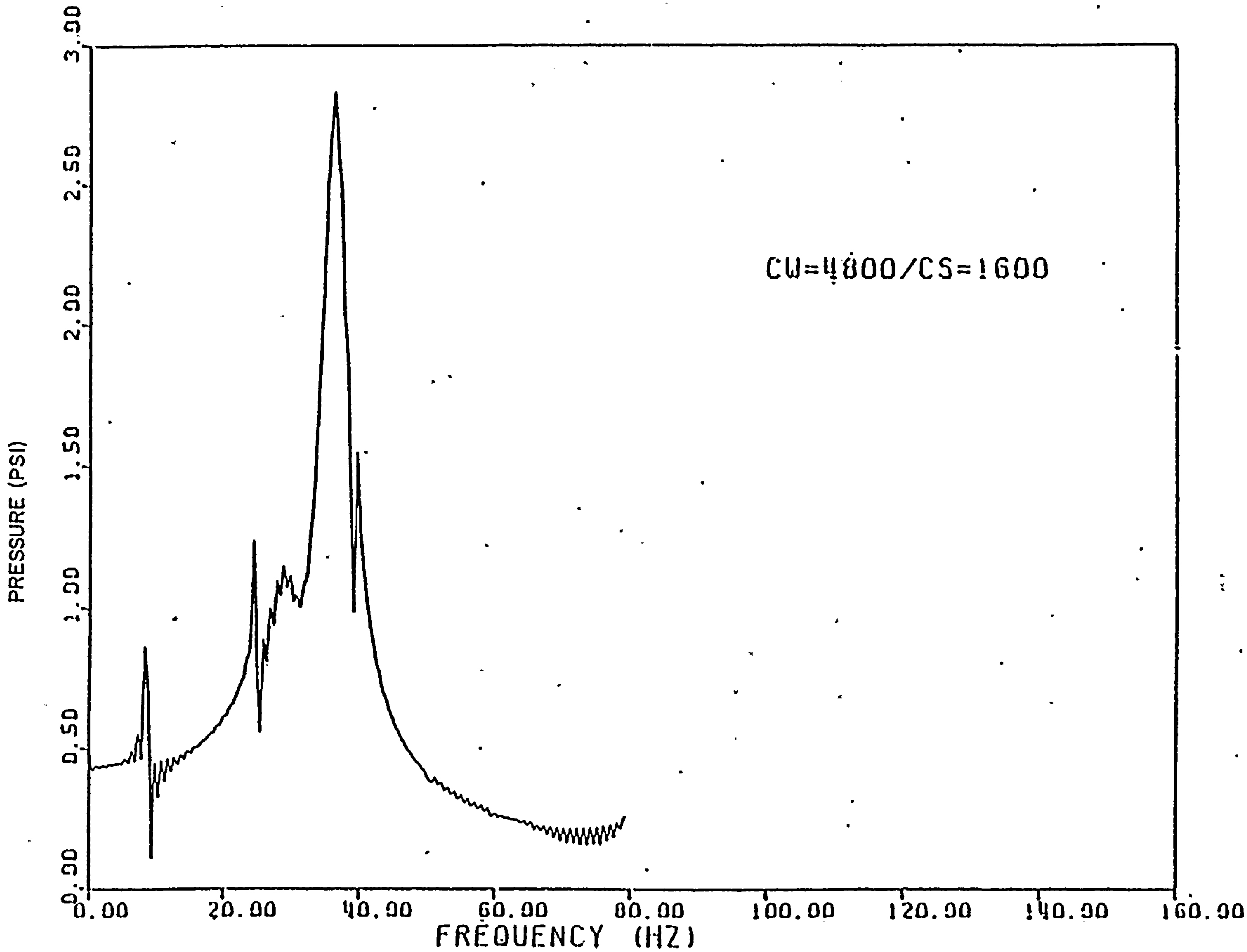




WASHINGTON PUBLIC POWER SUPPLY SYSTEM
NUCLEAR PROJECT NO. 2

FOURIER AMPLITUDE SPECTRUM OF PRESSURE CALCULATED @ CH.28 WITH ACCELERATION SOURCE LOC.6' ABOVE BOT.

FIGURE 3-22



WASHINGTON PUBLIC POWER SUPPLY SYSTEM
NUCLEAR PROJECT NO. 2

FOURIER AMPLITUDE SPECTRUM OF PRESS. CALCULATED @ CH.28 WITH ACCELERATION SOURCE LOCATED 3' ABOVE BOTTOM

FIGURE 3-23

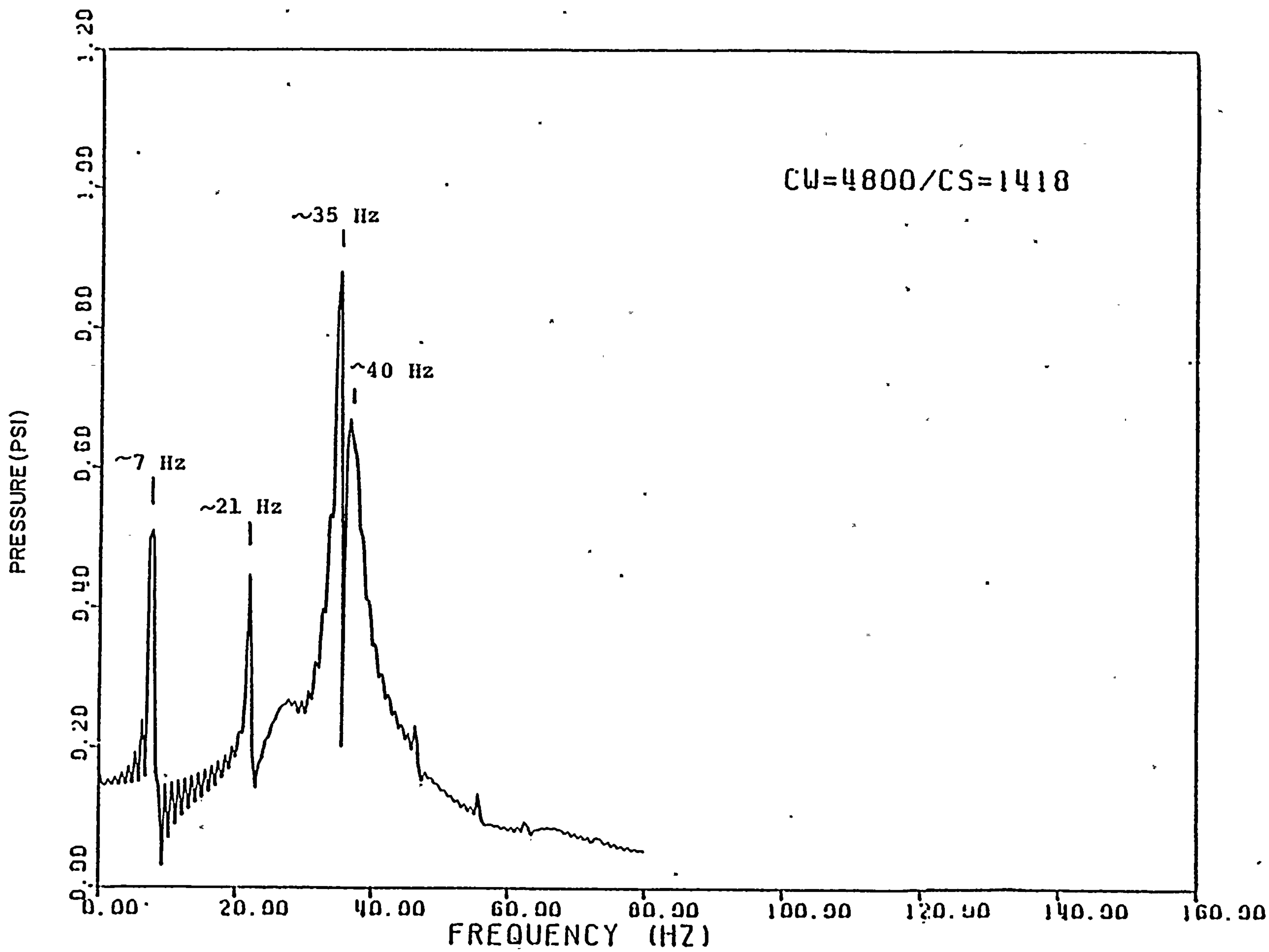
WASHINGTON PUBLIC POWER SUPPLY SYSTEM. NUCLEAR PROJECT NO. 2	COMPARISON OF VERTICAL DISTRIBUTION OF NORMALIZED MAX. PRESS. CALCULATED W/PRESS. & ACCELERATION SOURCES	FIGURE 3-24

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	VERT. DISTR. OF FOURIER AMPLITUDES OF PRESS. CALCULATED WITH ACCEL. SOURCE AT VENT EXIT	FIGURE 3-25

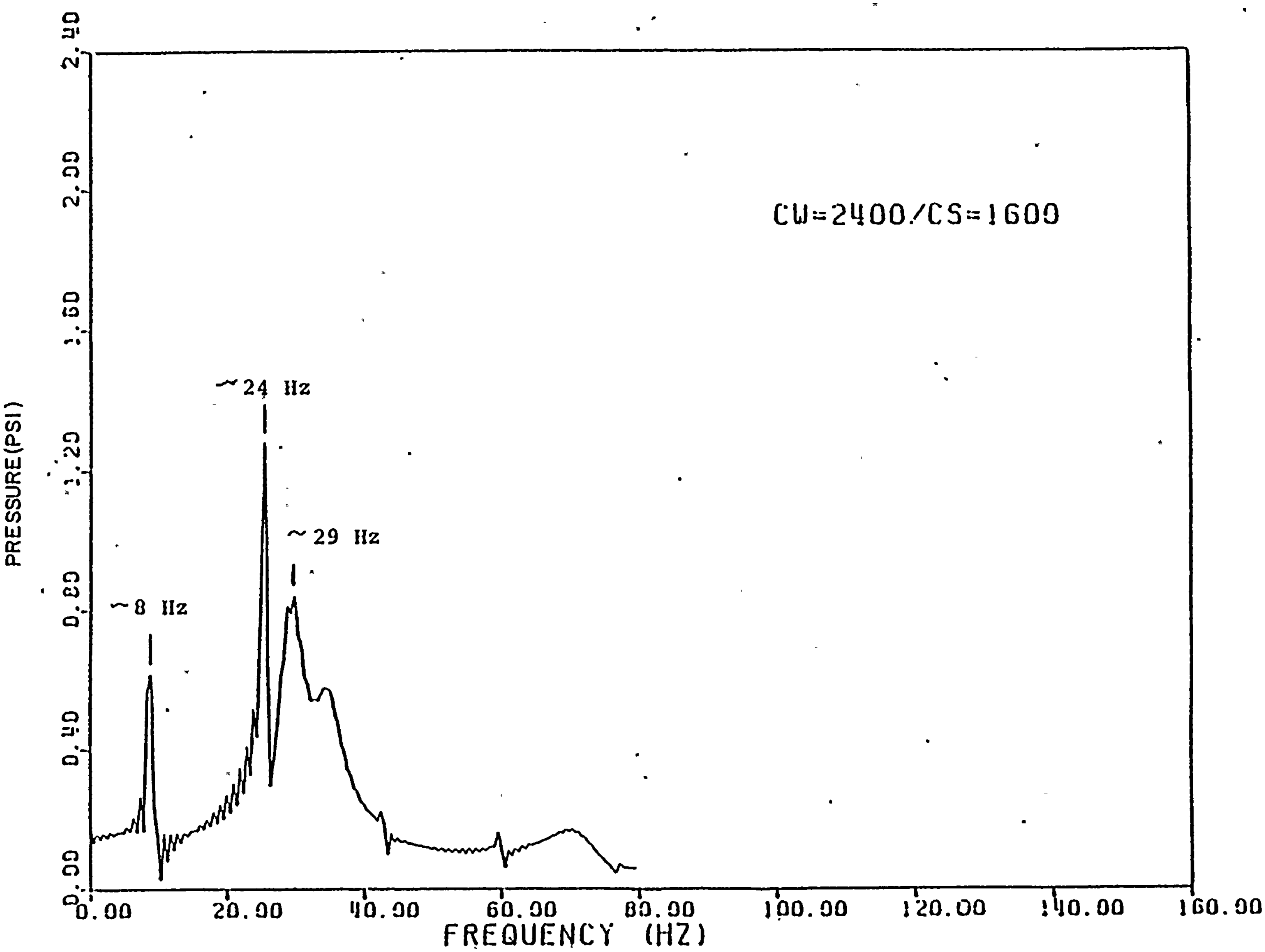
WASHINGTON PUBLIC POWER SUPPLY SYSTEM
NUCLEAR PROJECT NO. 2

FOURIER AMPLITUDE SPECTRUM OF PRESS.AT CH.28 WITH C_s=1418 fps, DECREASED FROM 1600 fps FIG.3-21

FIGURE 3-26



WASHINGTON PUBLIC POWER SUPPLY SYSTEM
NUCLEAR PROJECT NO. 2

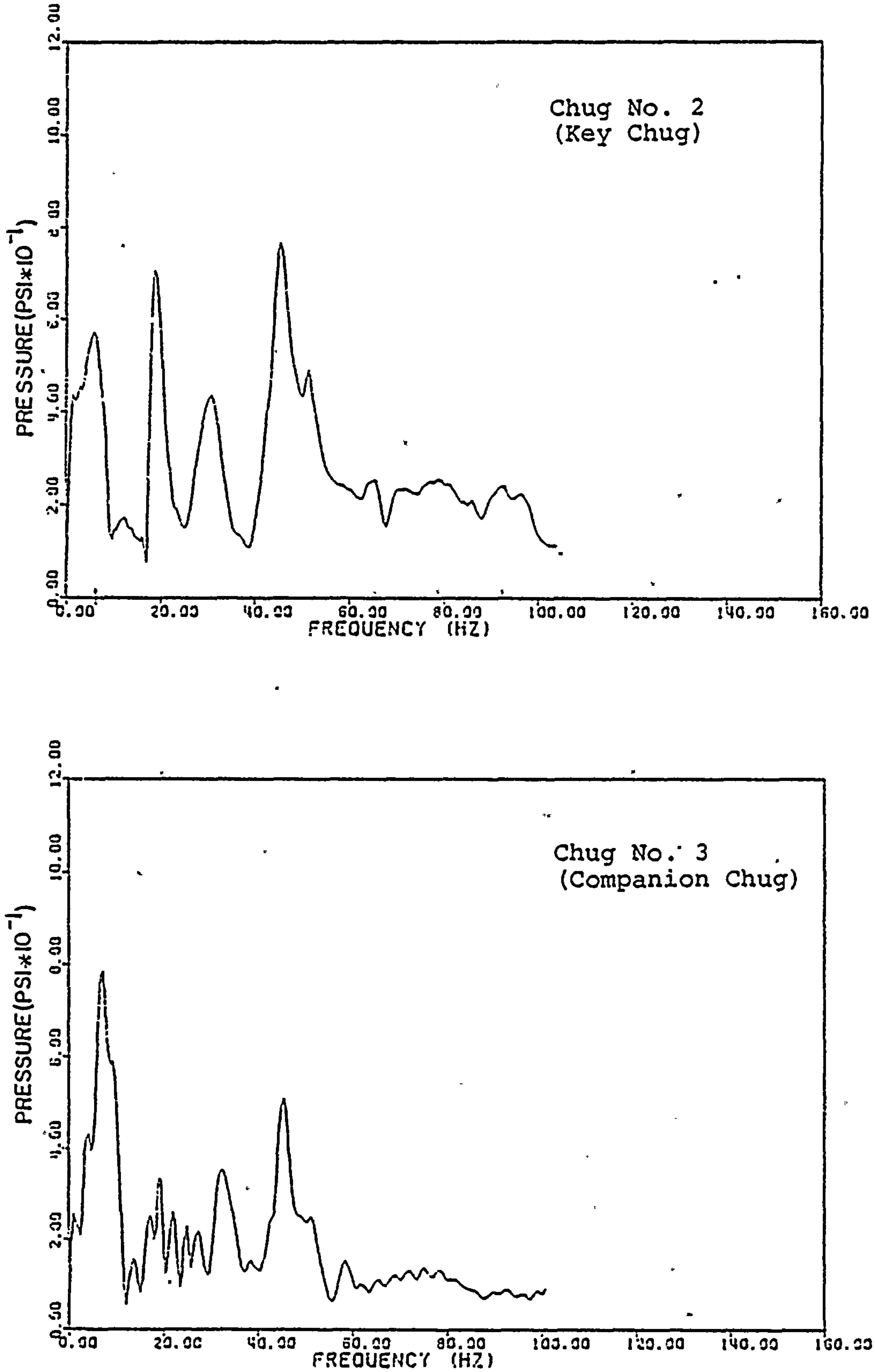


FOURIER AMPLITUDE SPECTRUM OF PRESSURE AT CH.28 WITH C_W=2400 fps, DECREASED FROM 4800 fps FIG.3-21

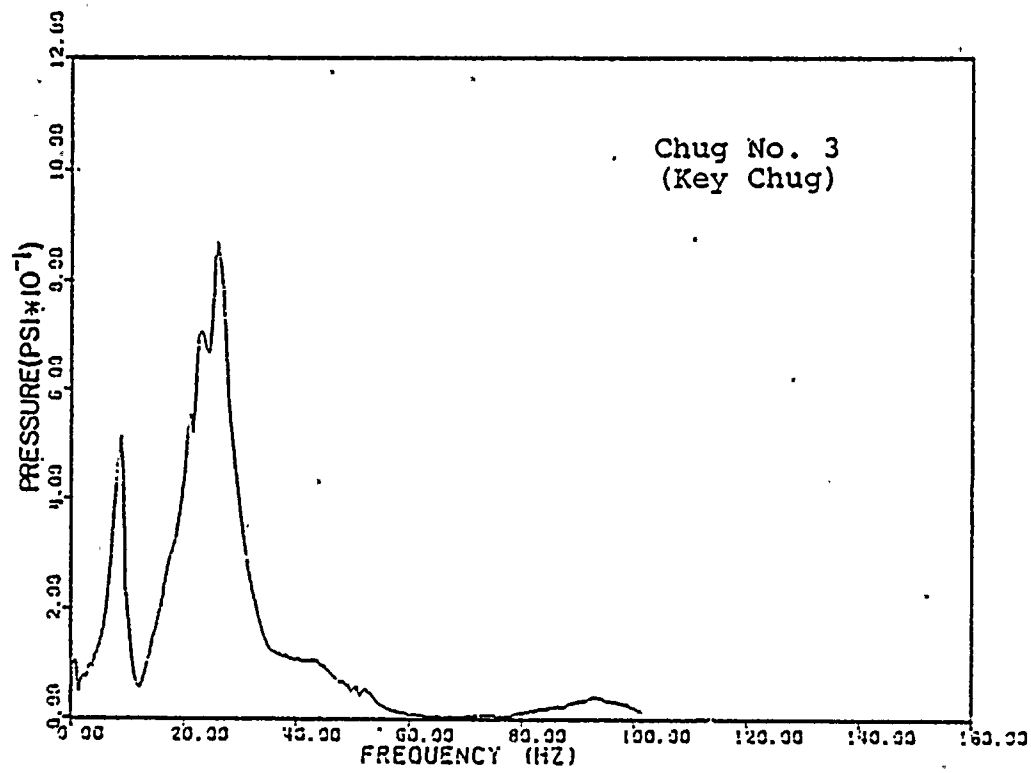
FIGURE 3-27

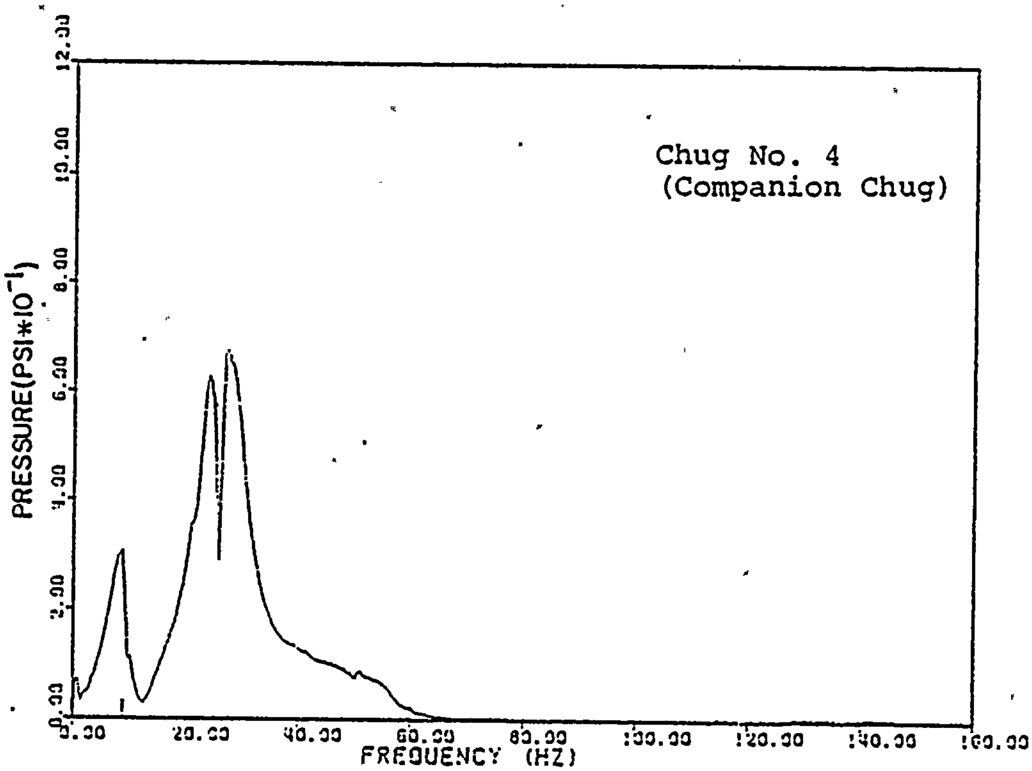
WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	PHASE RELATIONSHIP BETWEEN PRESSURES CALCULATED AT CH.20 AND CH.28 VS. FREQUENCY	FIGURE 3-28

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	C_v VS. RESONANT FREQUENCY - ANALYTICAL CURVE & ITS APPL.	FIGURE 3-29



WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	COMPARISON OF FOURIER SPECTRA OF PRESS. OF KEY CHUG & COMPANION CHUG MEASURED AT CH.28-TIME WINDOW NO.2	FIGURE 4-1





WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	COMPARISON OF FOURIER SPECTRA OF PRESS. OF KEY CHUG & COMPANION CHUG MEASURED AT CH.28, TIME WINDOW NO.3	FIGURE 4-2

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2.	DESIGN SPECTRUM AND REQUIRED AVERAGE SPECTRUM - CHANNEL 28	FIGURE 4-3

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2.	DESIGN SPECTRUM AND REQUIRED AVERAGE SPECTRUM - CHANNEL 26	FIGURE 4-4

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	DESIGN SPECTRUM AND REQUIRED AVERAGE SPECTRUM - CHANNEL 24	FIGURE 4-5

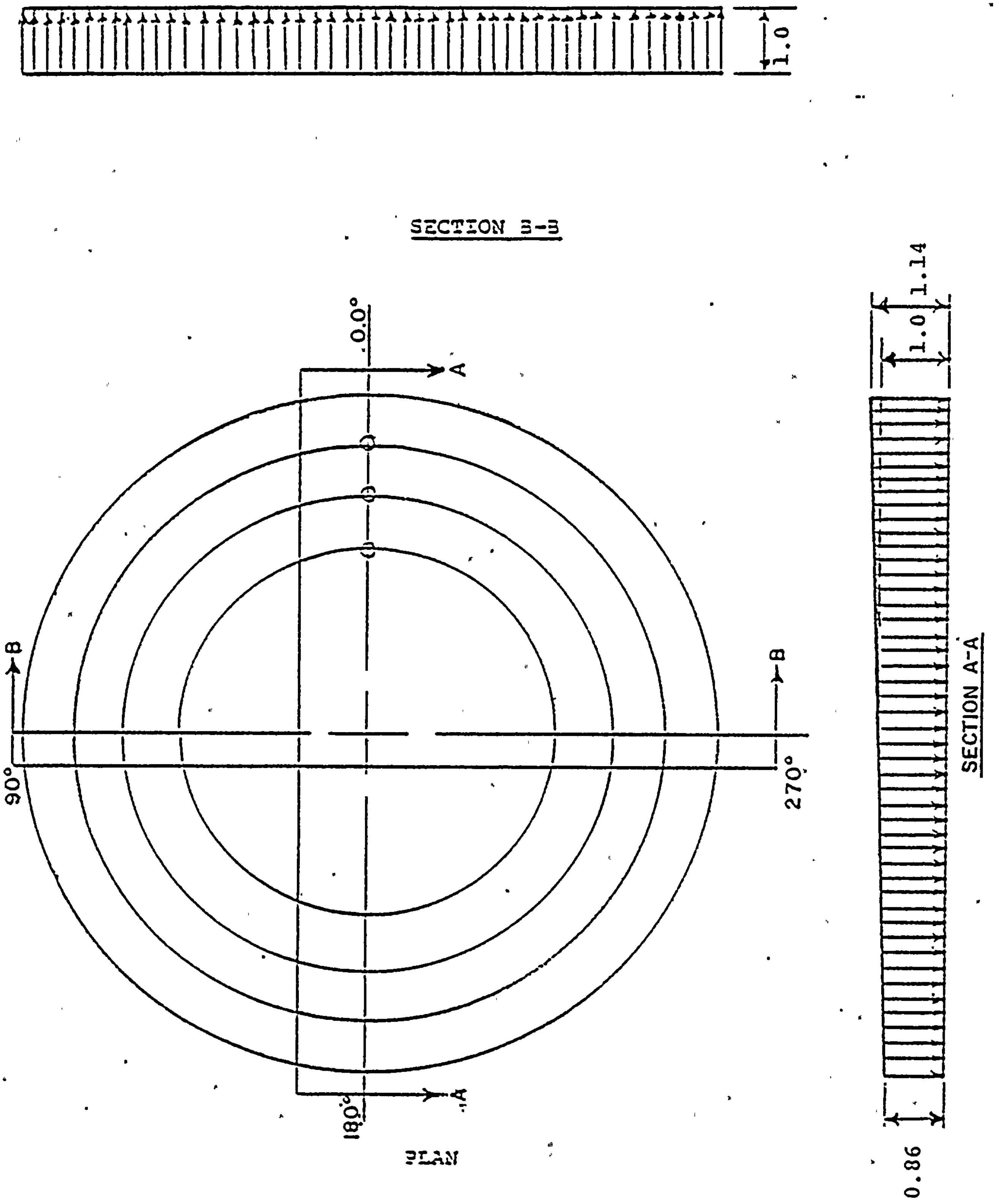
WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	DESIGN SPECTRUM AND REQUIRED AVERAGE SPECTRUM - CHANNEL 20	FIGURE 4-6

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2.	DESIGN SPECTRUM AND REQUIRED ENVELOPE SPECTRUM - CHANNEL 28	FIGURE 4-7

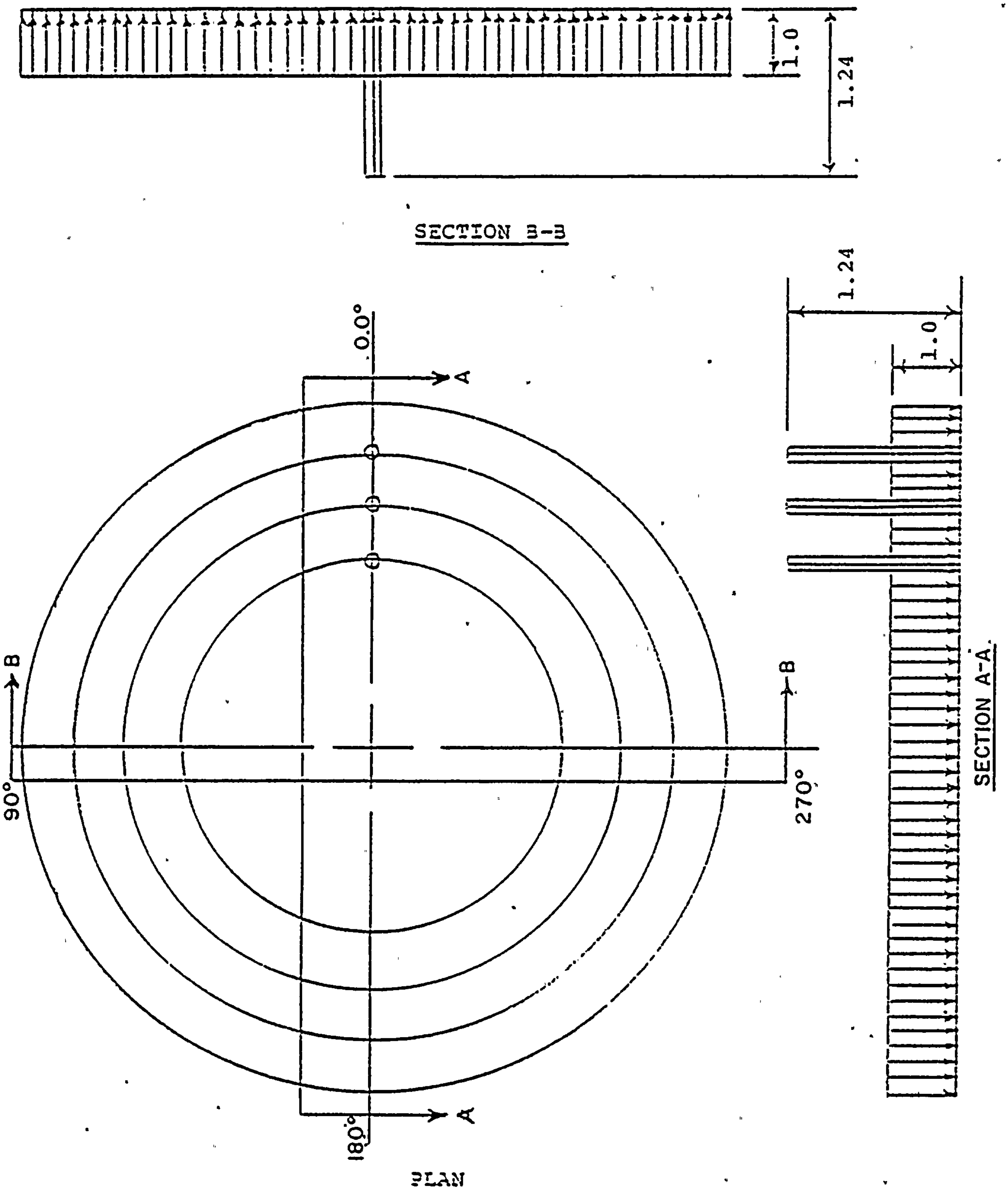
WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	DESIGN SPECTRUM AND REQUIRED ENVELOPE SPECTRUM - CHANNEL 26	FIGURE 4-8

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2.	DESIGN SPECTRUM AND REQUIRED ENVELOPE SPECTRUM - CHANNEL 24	FIGURE 4-9

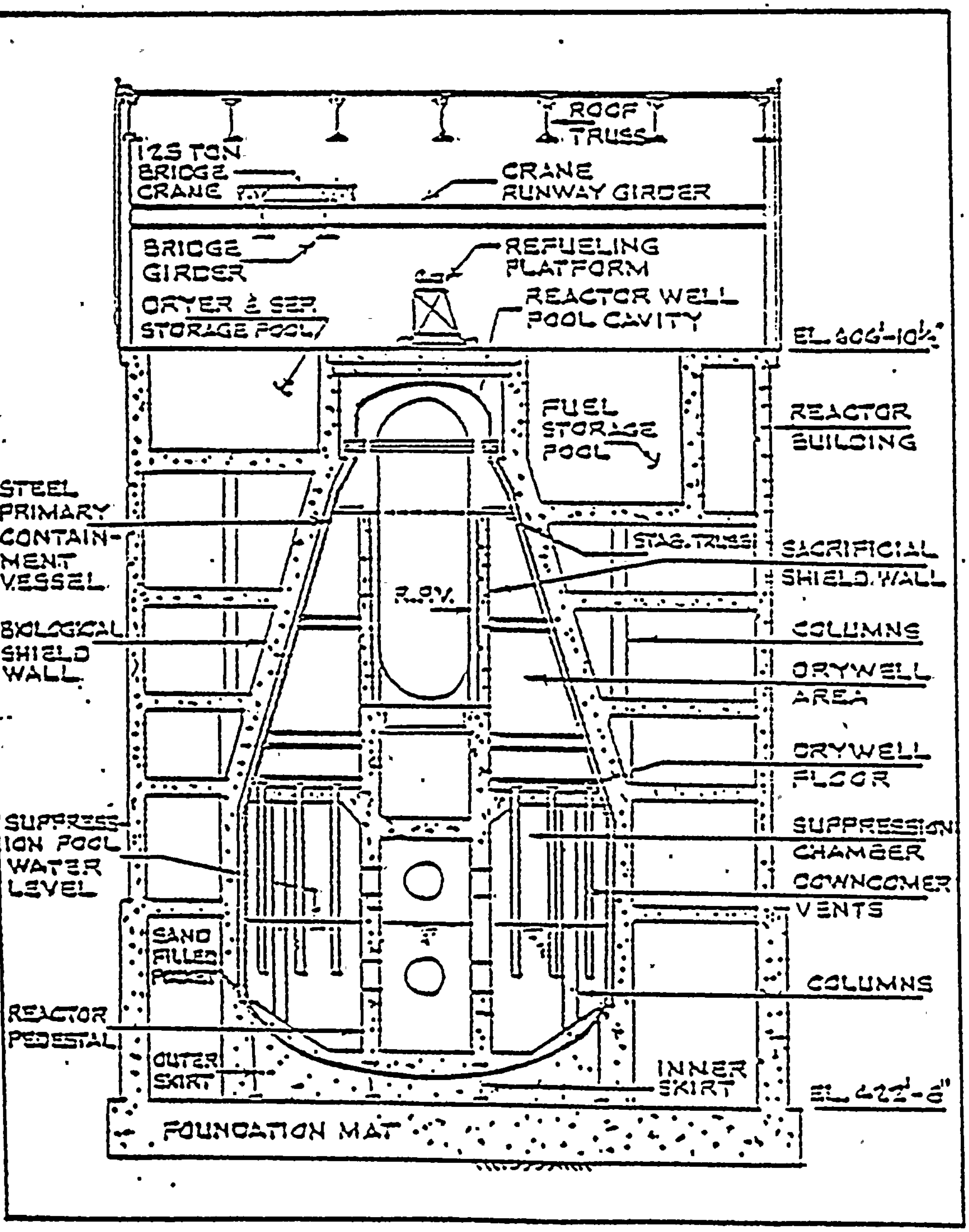
WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	DESIGN SPECTRUM AND REQUIRED ENVELOPE SPECTRUM - CHANNEL 20	FIGURE 4-10



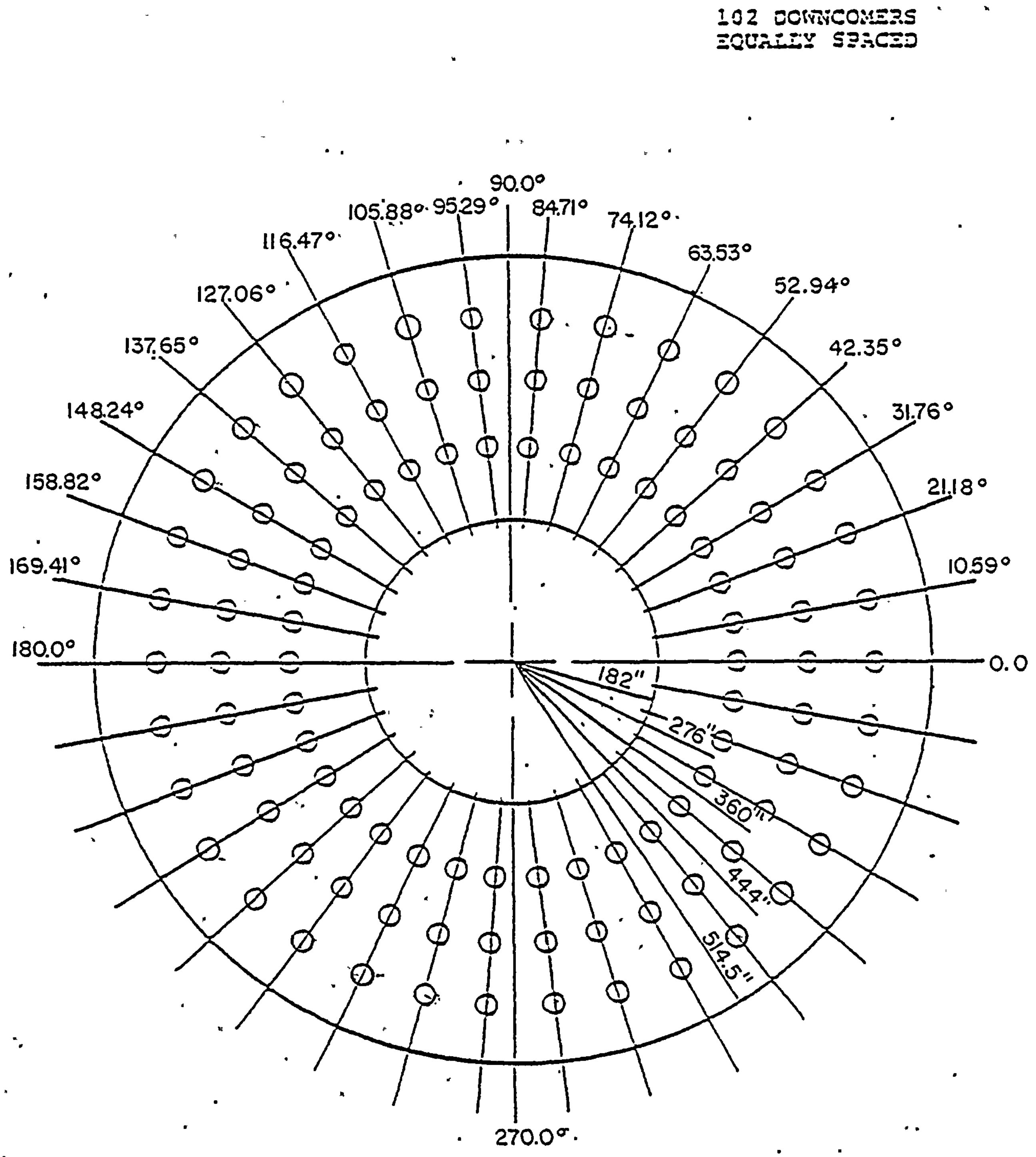
WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	SOURCE STRENGTH DISTRIBUTION - ASYMMETRIC LOADING CASE	FIGURE 4-11



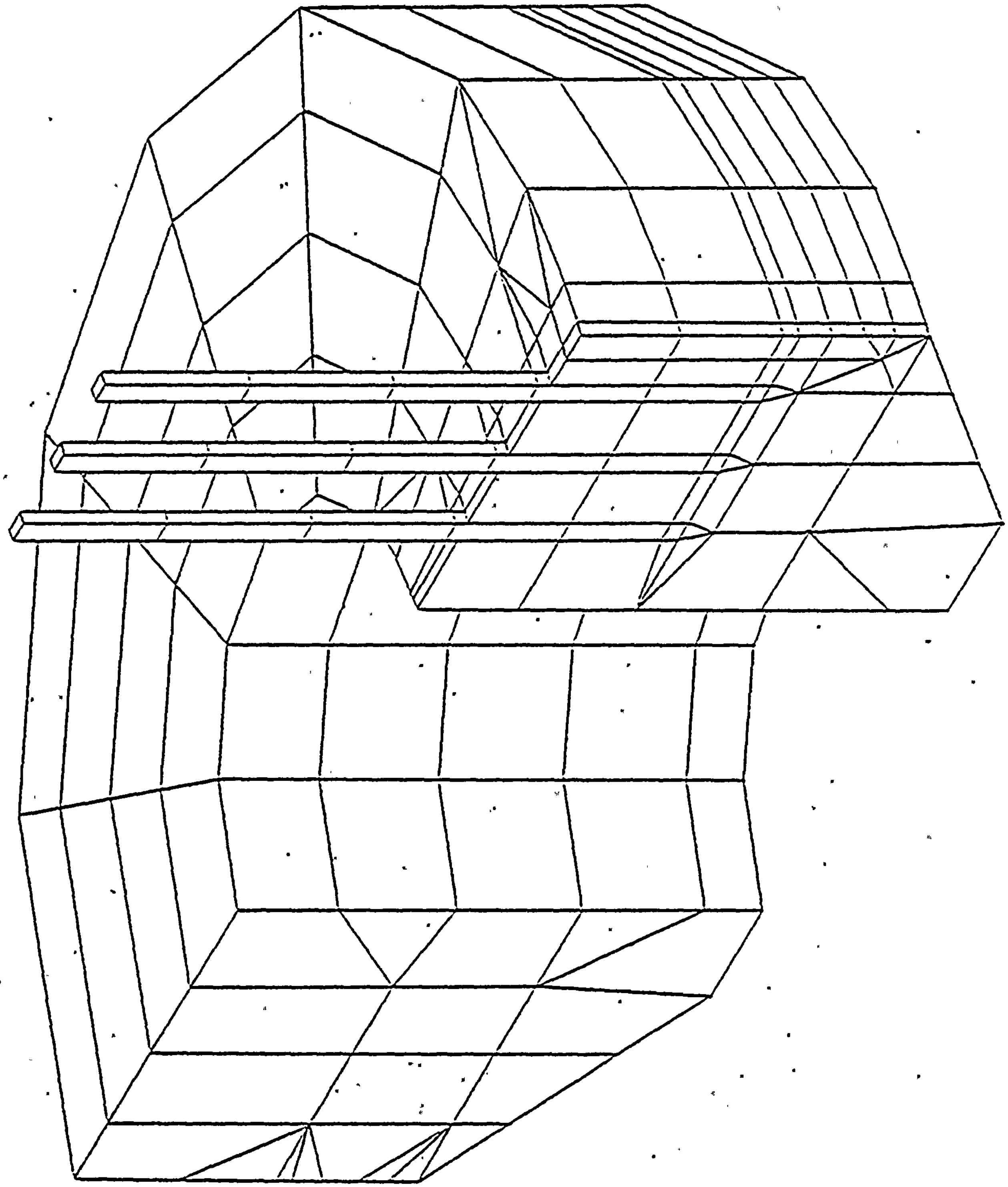
WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	SOURCE STRENGTH DISTRIBUTION - NEARLY SYMMETRIC LOADING CASE	FIGURE 4-12



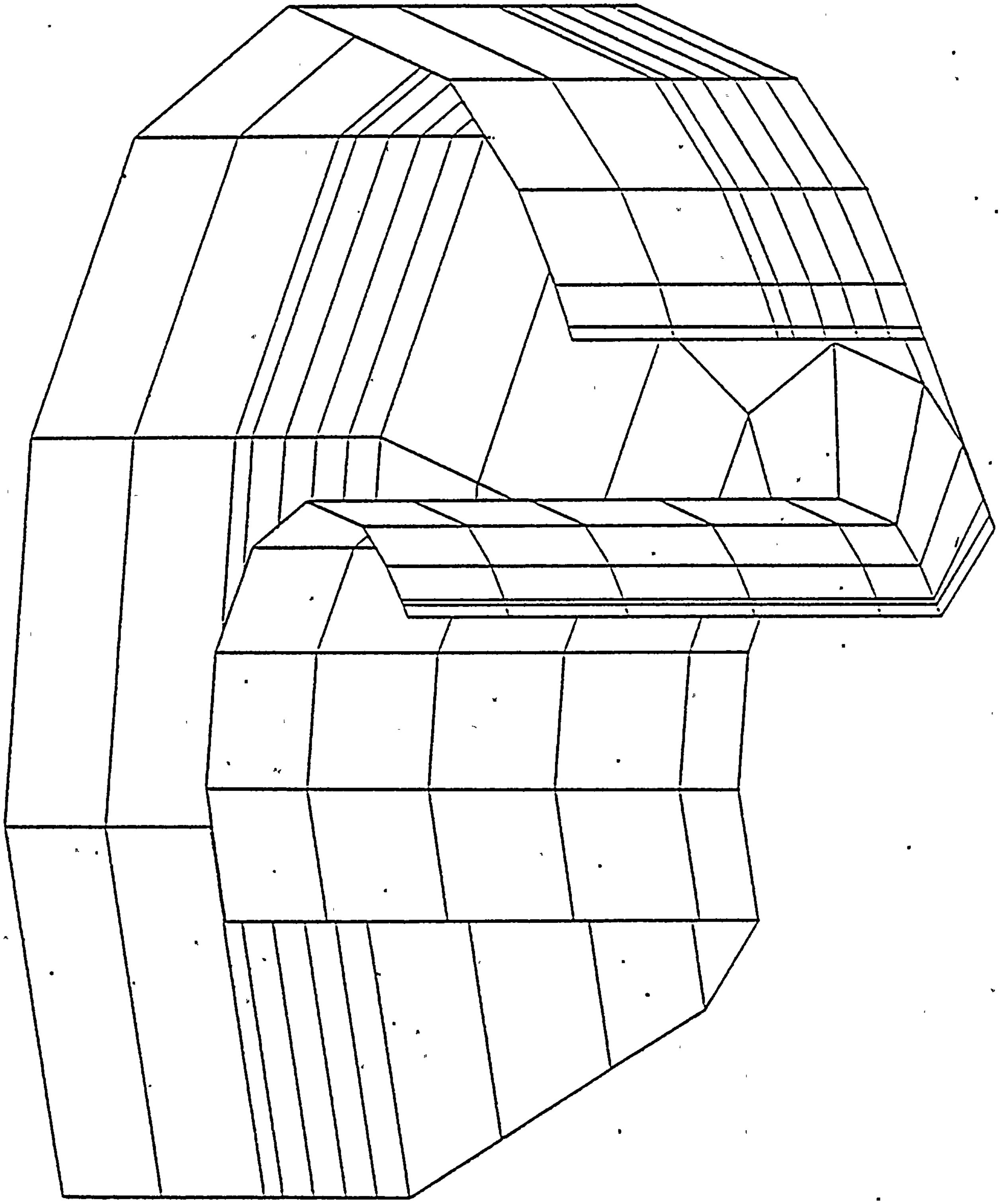
WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	GENERAL CROSS-SECTION OF WNP-2 REACTOR BUILDING	FIGURE 5-1



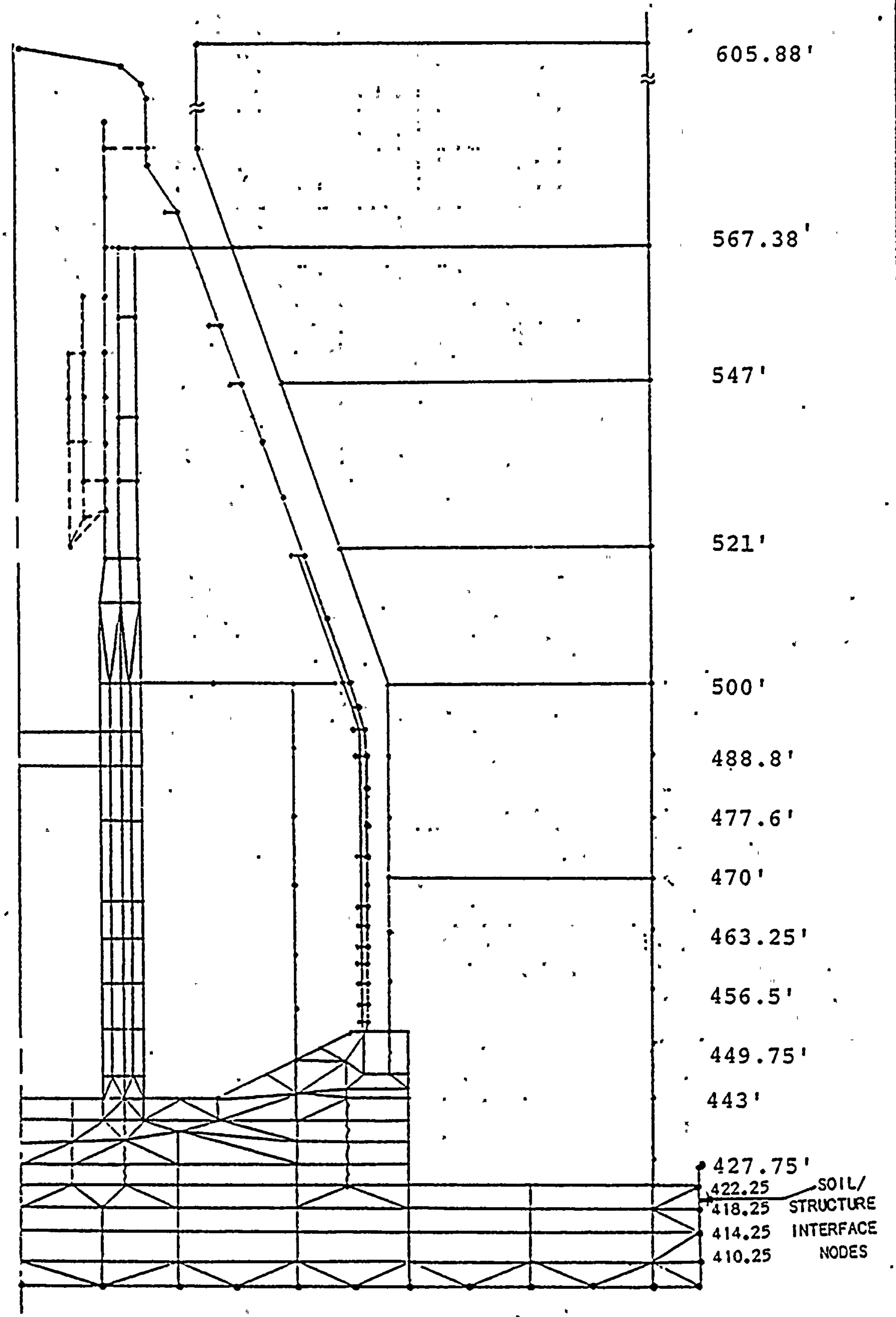
WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	WETWELL PLAN VIEW AT ELEVATION OF DOWNCOMER EXITS	FIGURE 5-2



WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2.	FINITE ELEMENT MODEL OF WNP-2 SUPPRESSION POOL WITH A RADIAL ROW OF THREE VENTS	FIGURE 5-3

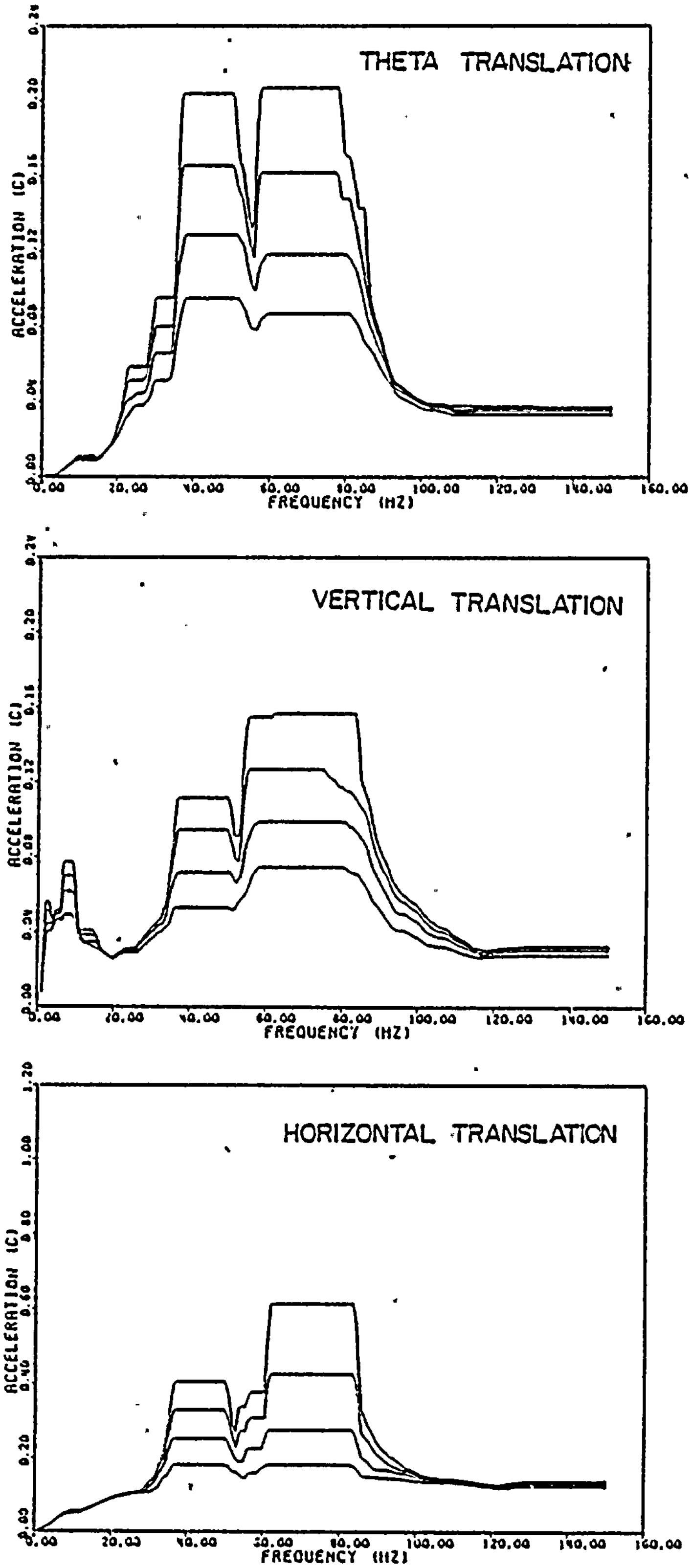


WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2.	FLUID-STRUCTURE BOUNDARY-WNP-2 SUPPRESSION POOL	FIGURE 5-4



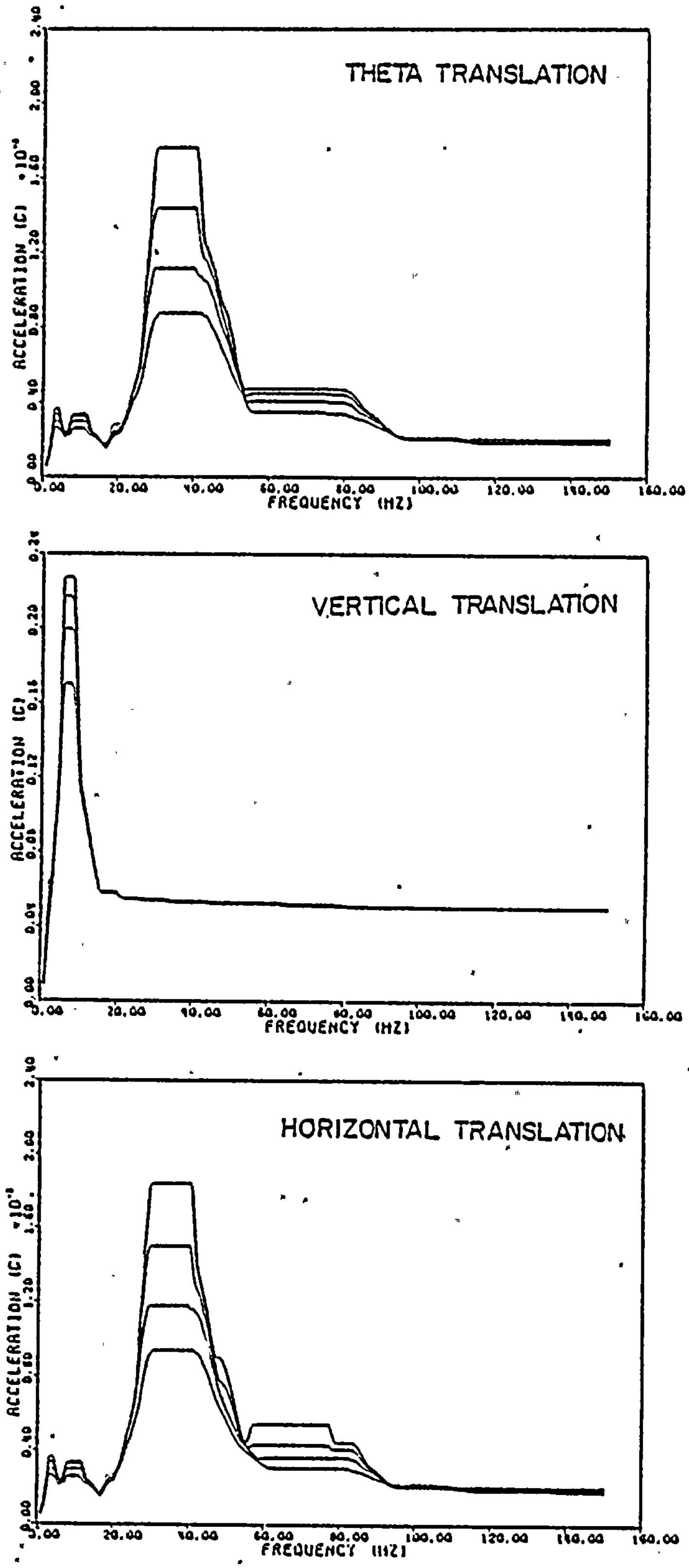
WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	REACTOR BUILDING MODEL	FIGURE 5-5

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	ENVELOPES OF CALCULATED RESPONSES FOR WNP-2 AND MEASURED RESPONSES AT JAERI-CONTAINMENT AT VENT EXIT ELEVATION	FIGURE 5-6



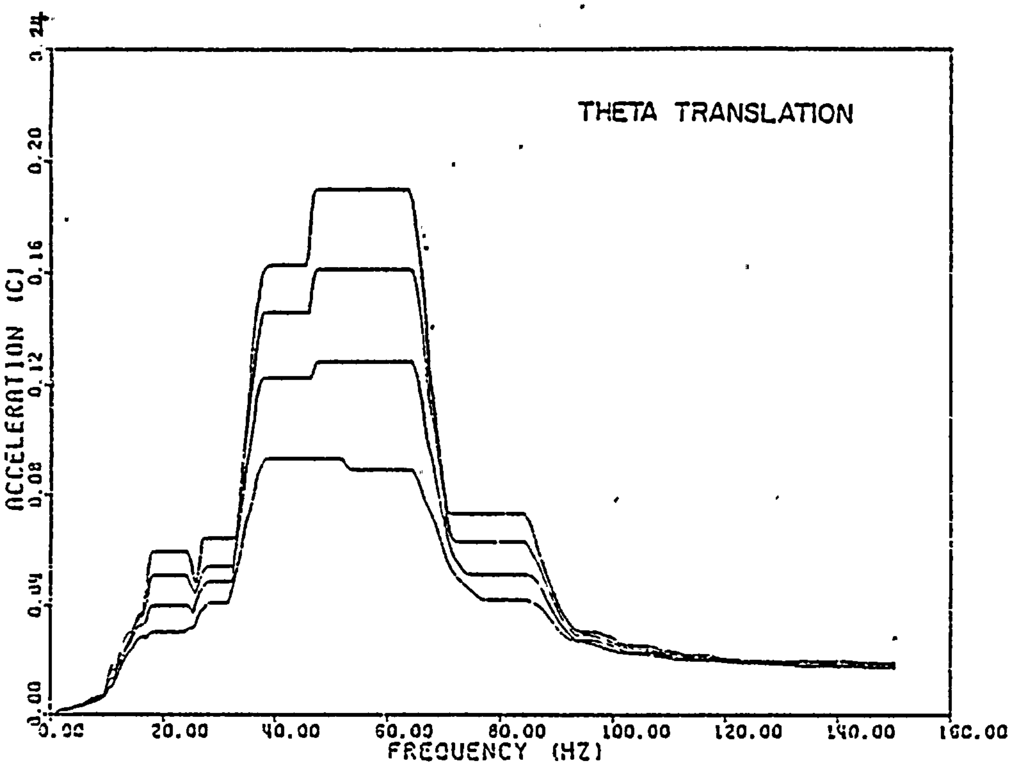
Note: Multiply all acceleration values by 1.18.

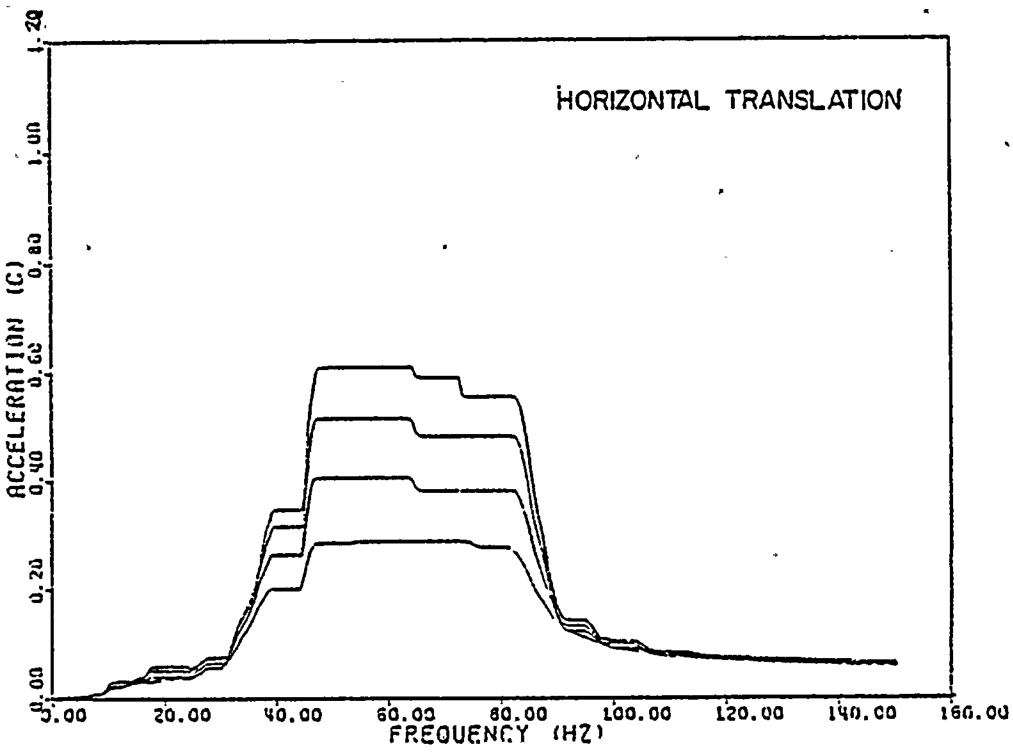
WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	REACTOR BUILDING RESPONSE - ASYMMETRIC LOADING: CONTAINMENT VESSEL AT MAT	FIGURE 5-7 a



Note: Multiply all acceleration values by 1.18.

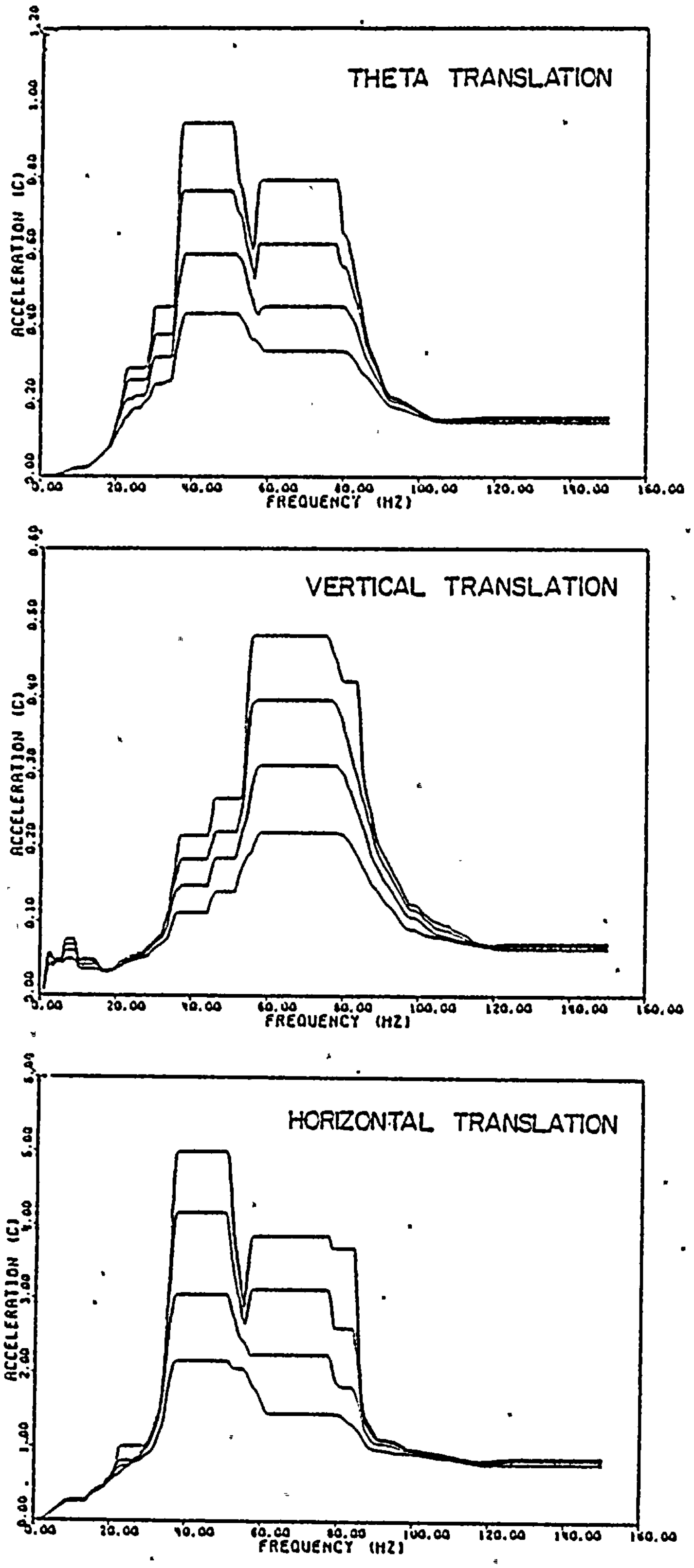
WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	REACTOR BUILDING RESPONSE - ASYMMETRIC LOADING: RPV SUPPORT	FIGURE 5-7b





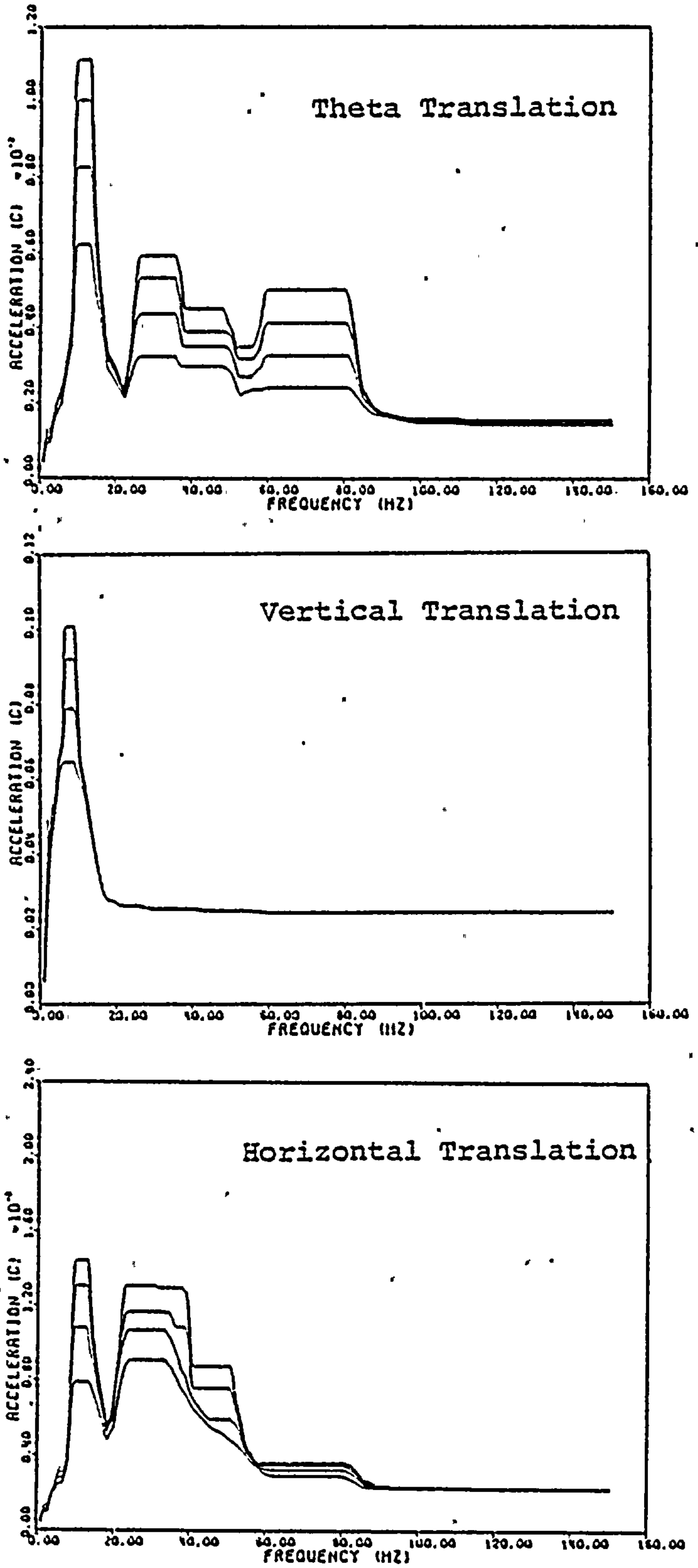
Note: Multiply all acceleration values by 1.18.

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	REACTOR BUILDING RESPONSE-ASYMMETRIC LOADING: CONTAINMENT VESSEL AT STABILIZER TRUSS LEVEL	FIGURE 5-7 c



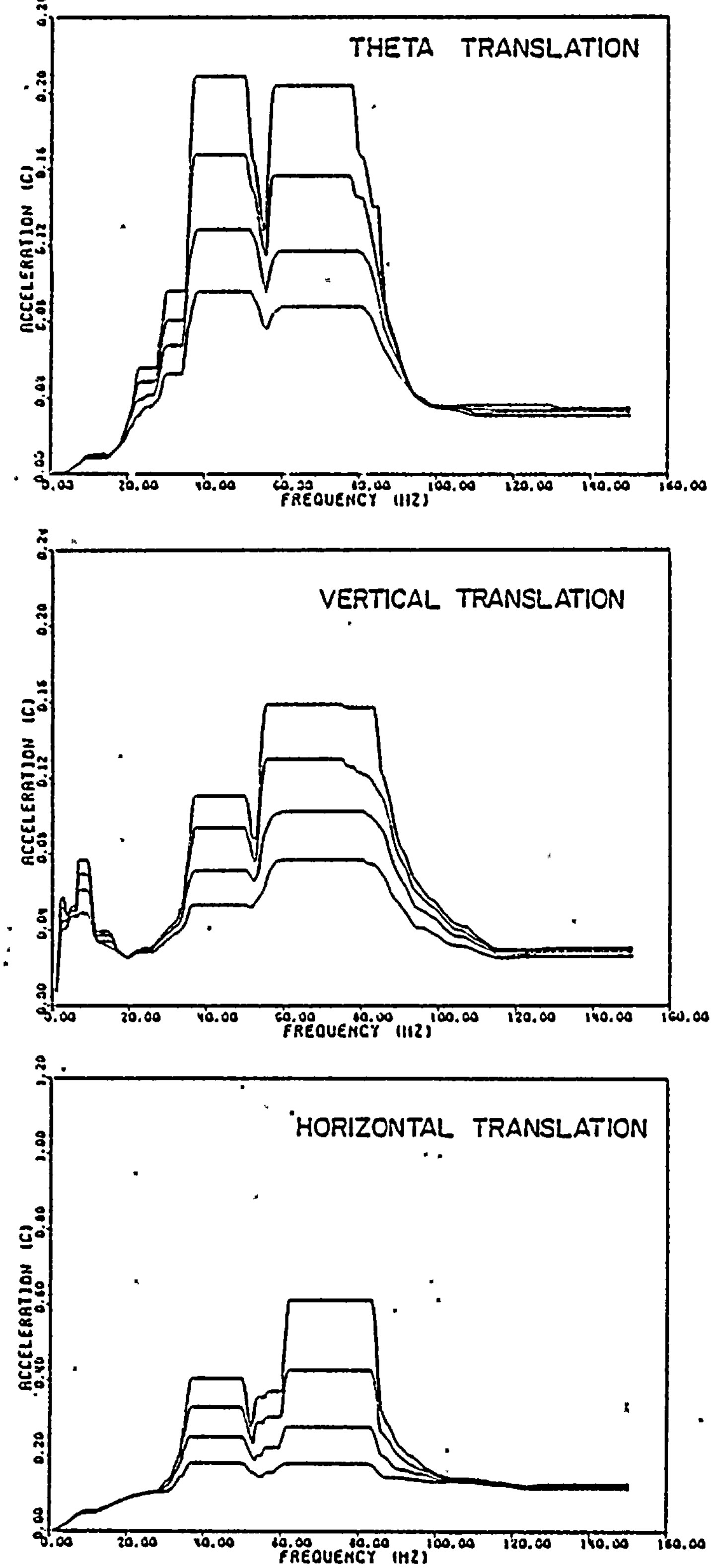
Note: Multiply all acceleration values by 1.18.

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	REACTOR BUILDING RESPONSE-ASYMMETRIC LOADING: CONTAINMENT VESSEL AT MID-SUBMERGENCE DEPTH	FIGURE 5-7 d



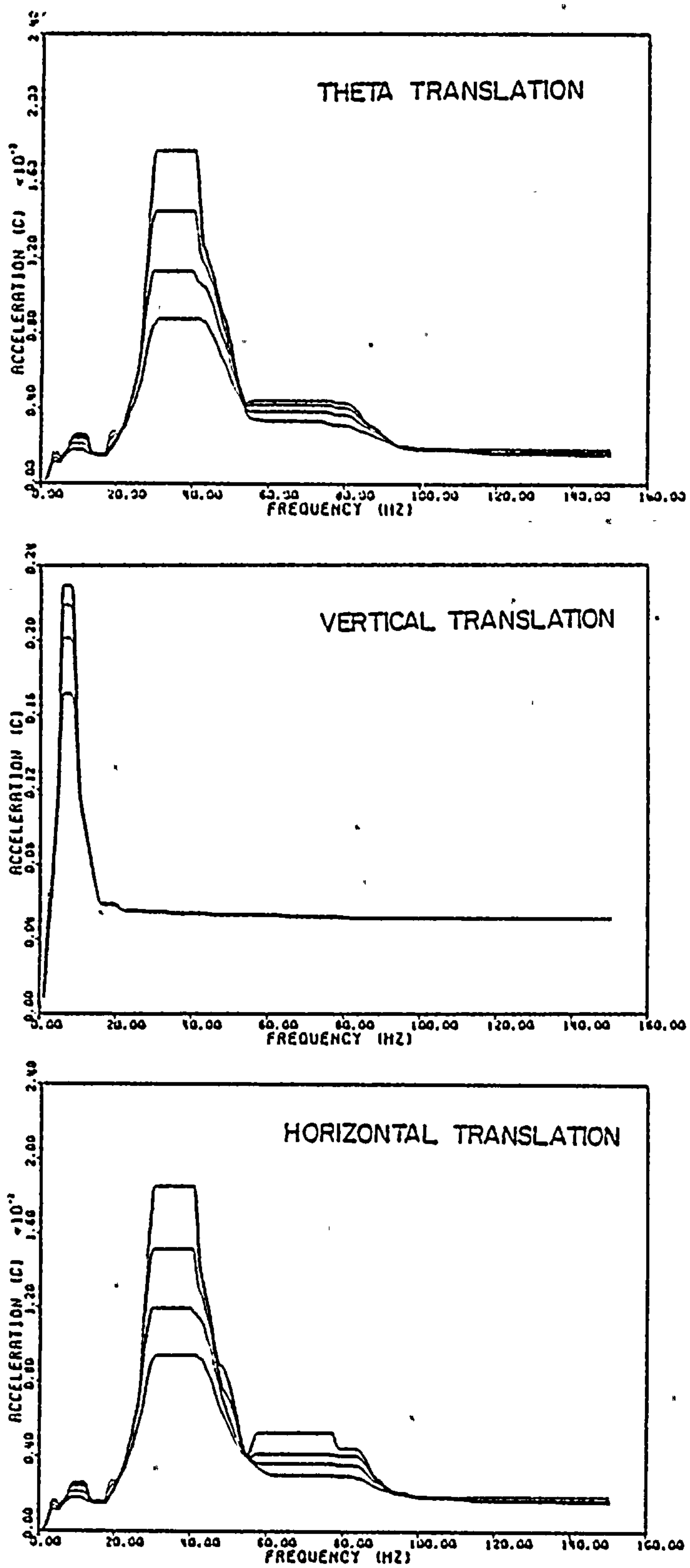
Note: Multiply all acceleration values by 1.18.

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	REACTOR BUILDING RESPONSE - ASYMMETRIC LOADING: OUTSIDE BUILDING WALL ELEVATION 521'	FIGURE 5-7e



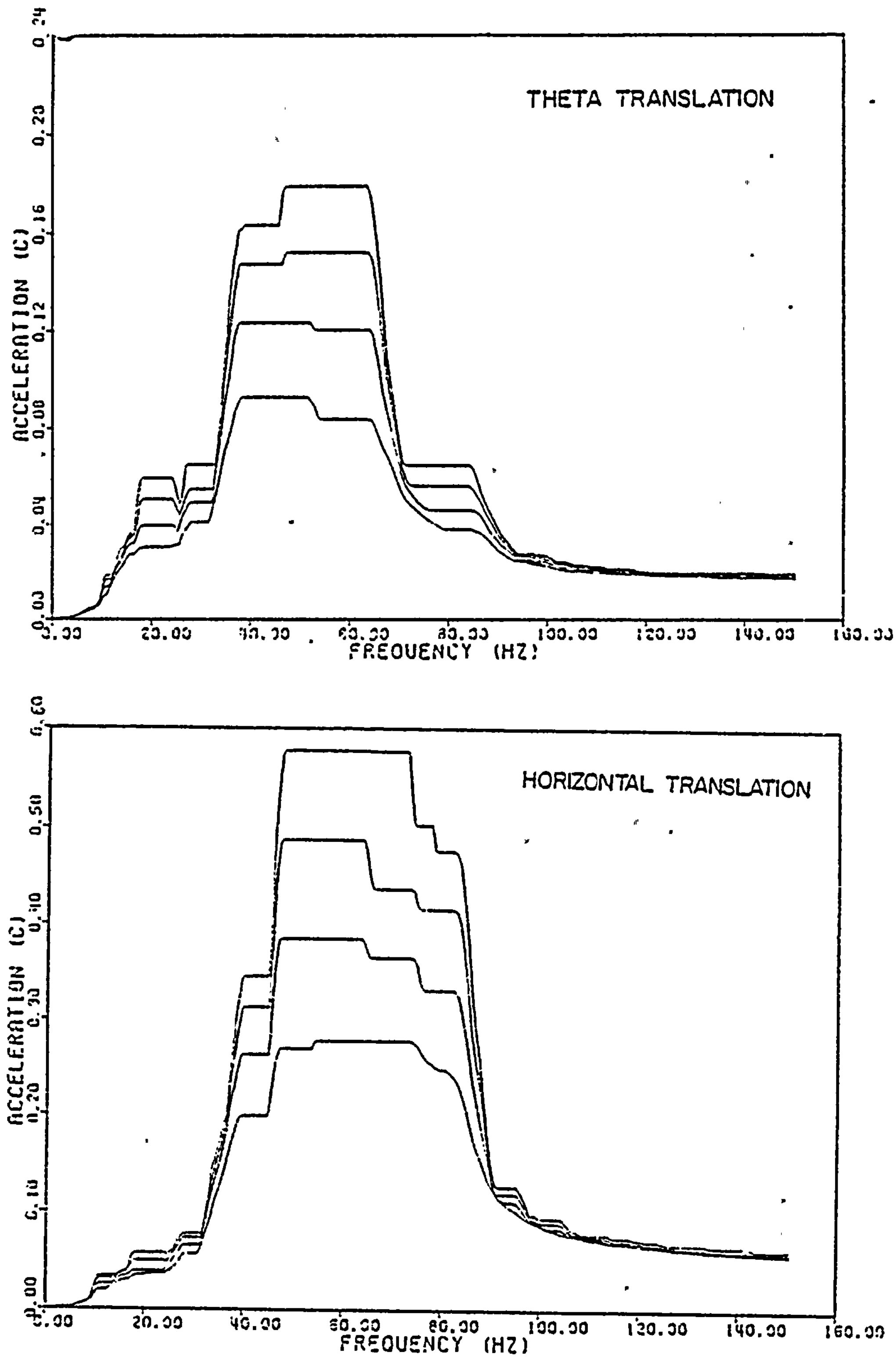
Note: Multiply all acceleration values by 1.18.

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	REACTOR BUILDING RESPONSE - NEARLY SYMMETRIC LOADING: CONTAINMENT VESSEL AT MAT	FIGURE 5-8a



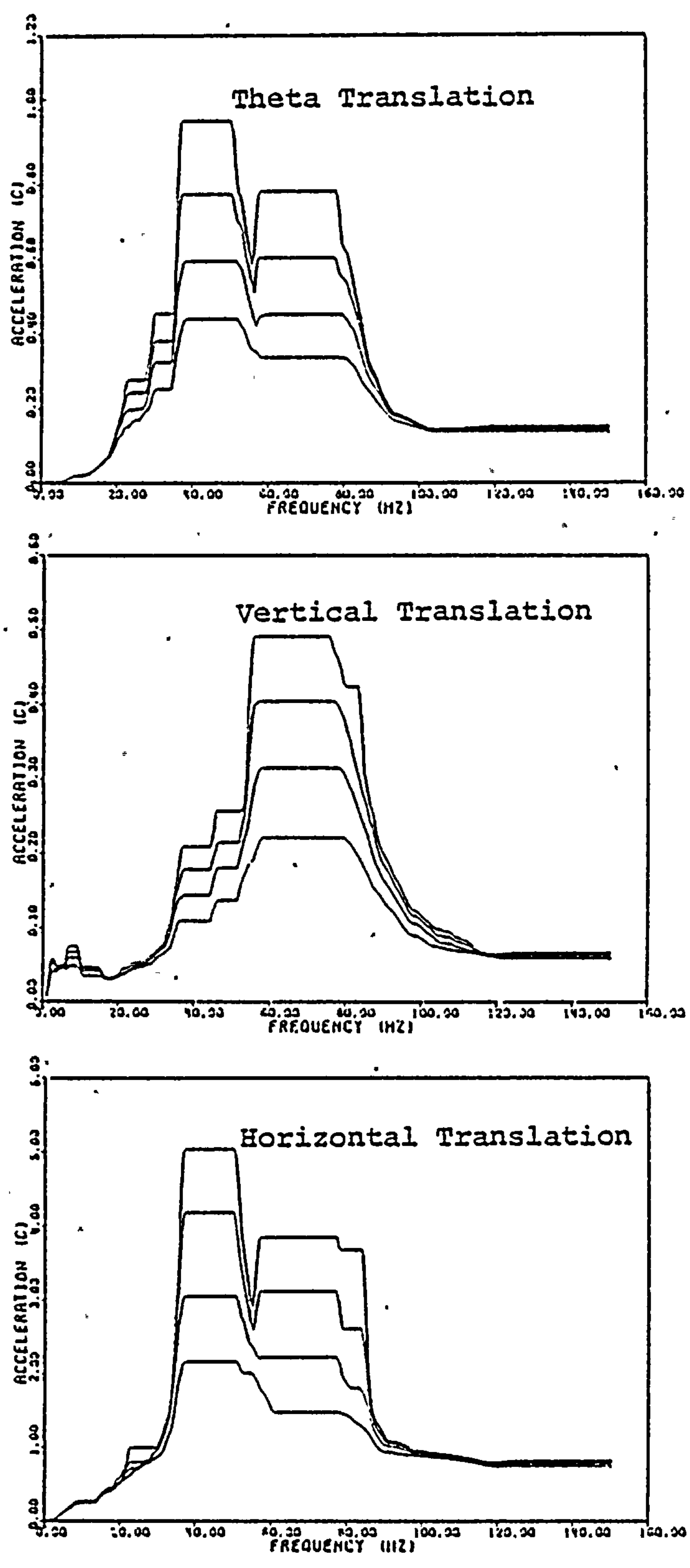
Note: Multiply all acceleration values by 1.18.

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	REACTOR BUILDING RESPONSE - NEARLY SYMMETRIC LOADING: RPV SUPPORT	FIGURE 5-8 b



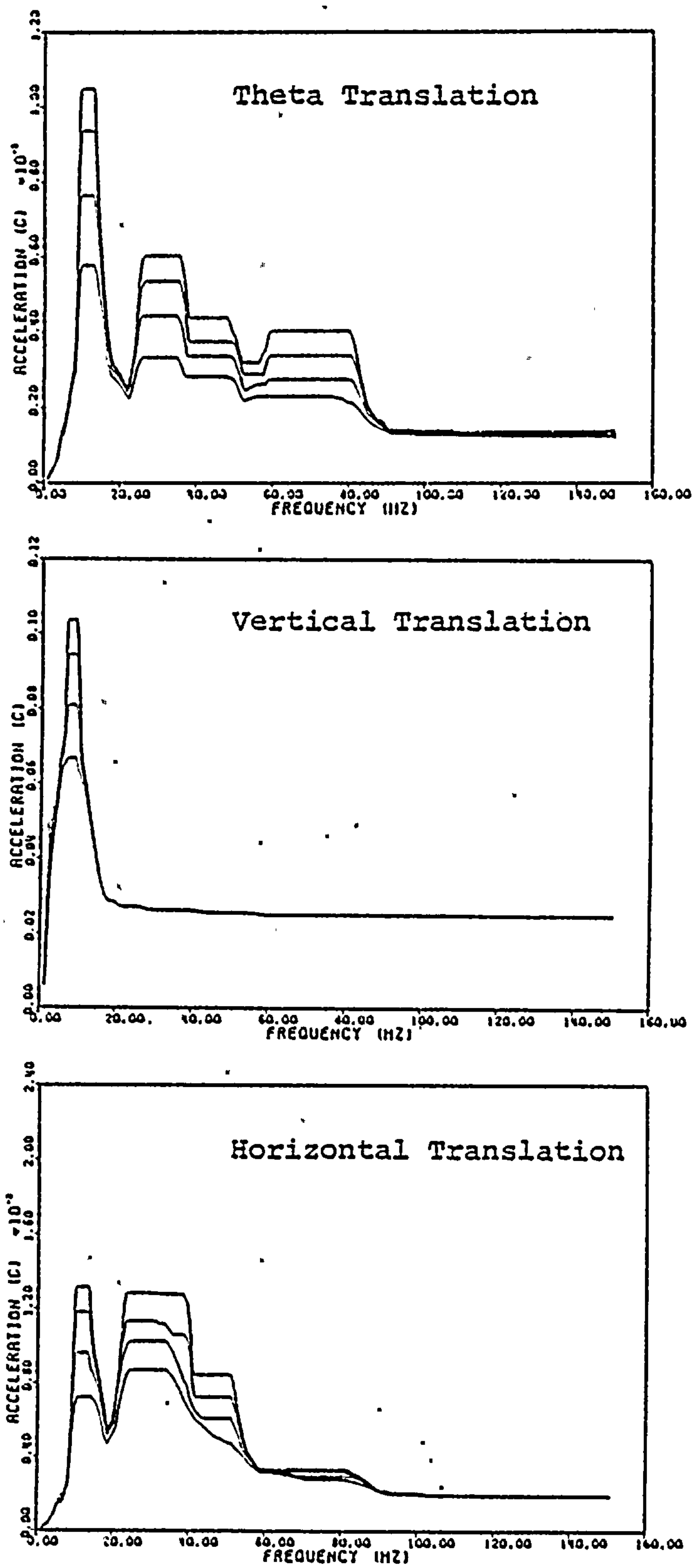
Note: Multiply all acceleration values by 1.18.

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	REACTOR BUILDING RESPONSE - NEARLY SYMMETRIC LOADING: CONTAINMENT VESSEL AT STABILIZER TRUSS LEVEL	FIGURE 5-8 c



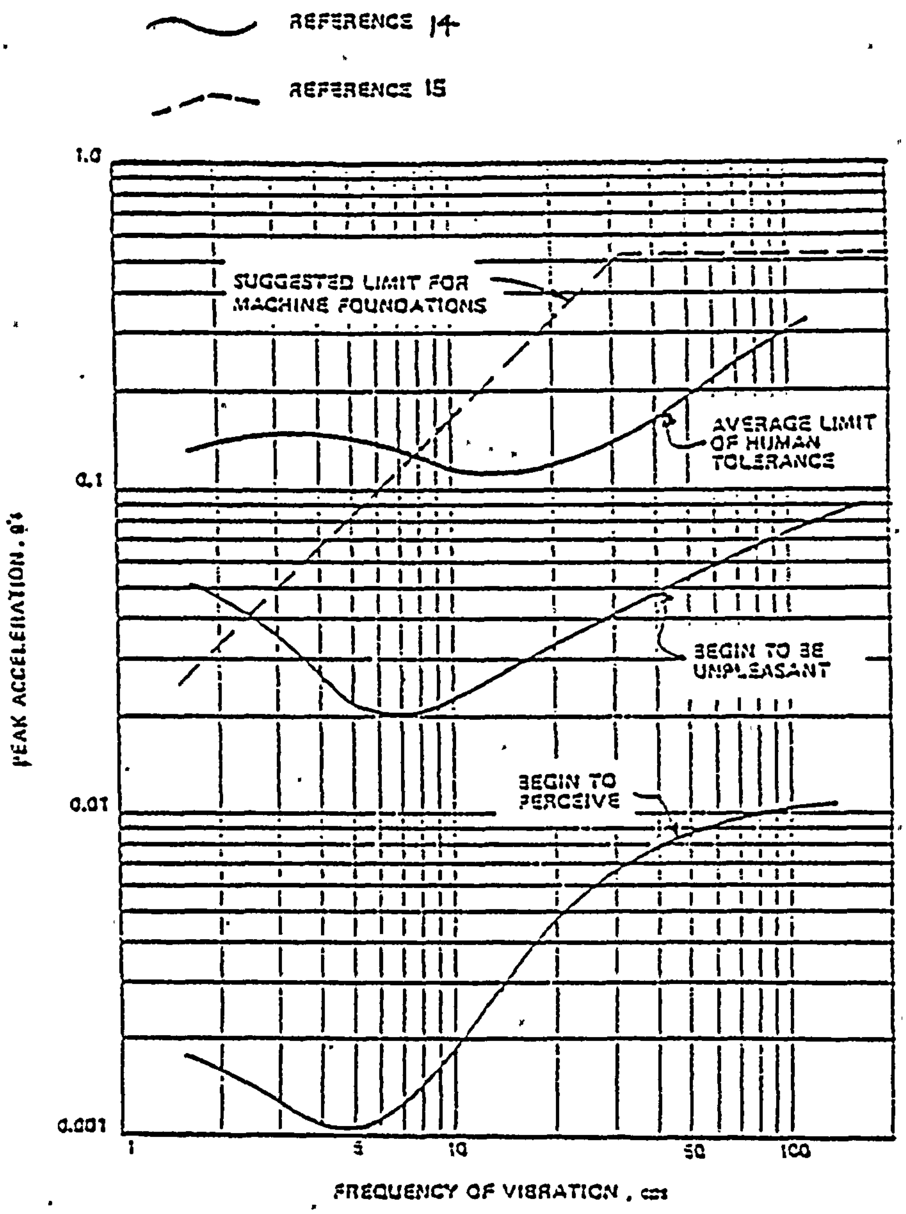
Note: Multiply all acceleration values by 1.18.

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	REACTOR BUILDING RESPONSE - NEARLY SYMMETRIC LOADING: CONTAINMENT VESSEL AT MID-SUBMERGENCE DEPTH	FIGURE 5-8 d



Note: Multiply all acceleration values by 1.18.

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	REACTOR BUILDING RESPONSE - NEARLY SYMMETRIC LOADING: OUTSIDE BUILDING WALL ELEVATION 521'	FIGURE 5-8e



WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	VIBRATION TOLERANCE OBSERVATIONS	FIGURE 5-9

APPENDIX A

ANALOGY BETWEEN ACOUSTIC AND STRUCTURAL BOUNDARY CONDITIONS

A.1 Introduction

Response of the analytical model of the 4T system to two types of sources, the pressure source and the acceleration source applied under the vent is presented in Section 3.3.2. It is shown that the two sources excite different modes of the 4T system. The difference in the excited modes is a result of different boundary conditions at the pool vent interface which appear in the analytical solutions of the two problems. It is important to recognize this basic difference between the two types of sources because the 4TCO key chugs which are simulated using the acceleration source contain the response of the system which cannot be simulated using the pressure source.

It is shown in this Appendix that the acceleration/pressure sources of vibration in acoustic fluid vibration problems are analogous to the force/displacement (or acceleration) sources in structural vibration problems. To emphasize the difference in the boundary conditions and their importance in changing the characteristics of the response, a simple structural vibration problem is first presented in this Appendix, then the anology is shown between the two problems.

A.2 Forced Longitudinal Vibrations of a Prismatic Bar

The equation of motion of longitudinal vibrations of a prismatic bar due to external force p(x)f(t) and the formulation of its solution is shown in Figure A-1.

The eigenmodes and eigenvalues (frequencies) for two cases of boundary conditions are shown in Figure A-2. It is seen that the fundamental mode frequency for Case 1 (fixed-free) is one half of the fundamental mode frequency for Case 2 (fixed-fixed). It is shown in Figure A-3 that vibration of the bar due to a force applied at the free end is completely defined by the eigenmodes and frequencies corresponding to the Case 1 whereas the vibration of the bar due to a displacement motion prescribed at the free end is defined by the eigenmodes and frequencies corresponding to the Case 2. In other words, the characteristics of response of the bar due to an external force is completely different from the characteristics of response of the same bar due to an imposed (displacement) motion. The imposed displacement motion requires a change in the boundary condition at the location of imposed motion which alters the response characteristics of the system.

A.3 Analogy Between Acoustic Fluid Vibrations and Structural Vibrations

The equation of motion for the longitudinal vibrations of a prismatic bar is analogous to the equation of motion of acoustic fluid.

$$-\nabla^2 p\ (x,t) + \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = 0 \equiv -\frac{\partial^2 u}{\partial x^2} + \frac{1}{a^2}\frac{\partial^2 u}{\partial t^2} = 0$$

where $p \equiv u$

and $\nabla p \equiv \frac{\partial u}{\partial x}$ (note: $\frac{\partial u}{\partial x} = \epsilon_x = \frac{\sigma}{E} = \frac{P}{AE}$)

∴ Pressure Source in Acoustic Fluid Problems ≡ Imposed Displacement in Structural Vibration Problems

and Acceleration (or pressure gradient) Source in Acoustic Fluid Problems ≡ Applied force in Structural Vibration Problems

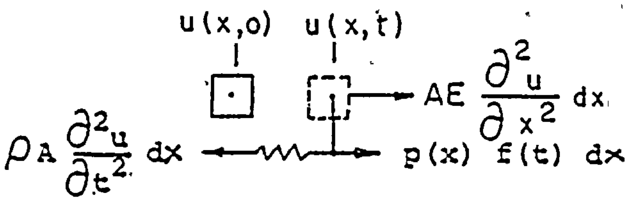
A.4 Conclusion

From the above analogy, it is evident that the response characteristics of acoustic fluid system excited by an acceleration source (which is analogous to externally applied force in structural vibrations) will be different from those excited by pressure source (which is analogous to imposed motion in structural vibrations).

Since key chugs are properly simulated using acceleration source, for chugging load definition to bound the key chug data, an acceleration source must be used.

A.5 References:

A-1 "Vibration Problems in Engineering", Timoshenko, S., D. Van Nostrand Company, Inc.



FORCES ACTING ON ELEMENT dx AT (x, t) (SEE SKETCH OF THE BAR BELOW)

Solution from Reference A-1 may be summarized as follows:

$$- AE \frac{\partial^2 u(x,t)}{\partial x^2} + A\rho \frac{\partial^2 u(x,t)}{\partial t^2} = p(x)\ f(t) \qquad \text{Equation of Motion (A-1)}$$

$$u(x,t) = \sum_{n=1,\ldots} X_n(x)\ \phi_n(t) \qquad \text{Solution for Homogeneous Boundary Conditions (A-2)}$$

$X_n(x)$ = Eigenmodes of the eigenvalue equation $X_n''(x) + K_n^2 X_n(x) = 0$ with appropriate homogeneous boundary conditions (e.g., Case 1 and 2 in Figure A-2)

$\phi_n(t)$ = Solution of the equation of motion $\ddot{\phi}_n(t) + \omega_n^2 \phi_n = p_n\ f(t)/A\rho$ with appropriate initial conditions

where, $a^2 = E/\rho$

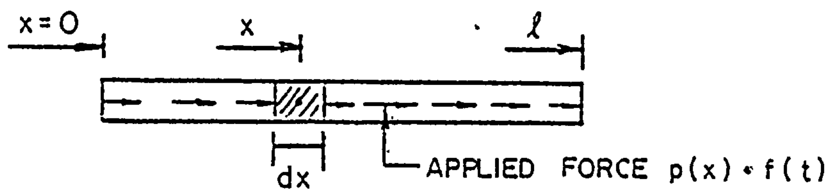
ω_n = frequency of vibration of natural mode n = $K_n a$

$$p_n = \int_0^{\ell} p(x)\ X_n(x)\ dx \Big/ \int_0^{\ell} X_n(x)^2\ dx$$

$$\phi_n(t) = A_n \cos\omega_n t + B_n \sin\omega_n t$$

$$+ \frac{p_n}{\omega_n A \rho} \int_0^t f(t_1) \sin\omega_n (t-t_1)\ dt_1 \qquad \text{(A-3)}$$

where constants A_n, B_n are obtained from initial conditions and are set equal to zero for the system at rest at t=0.



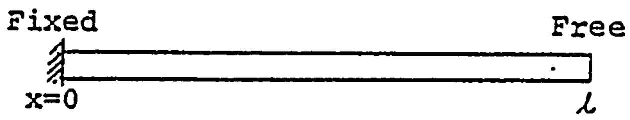
ρ = MASS DENSITY

E = MODULUS OF ELASTICITY

A = AREA OF CROSS SECTION

WASHINGTON PUBLIC POWER SUPPLY SYSTEM NUCLEAR PROJECT NO. 2	LONGITUDINAL TRANSIENT VIBRATIONS OF A PRISMATIC BAR	FIGURE A-1

Case 1



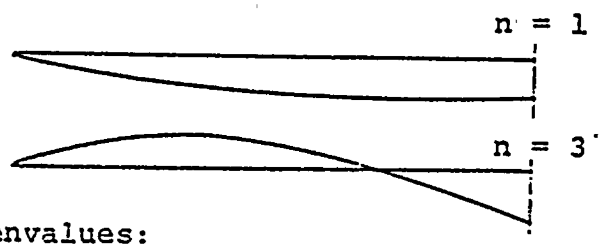
Boundary Conditions:

$$U(0) = 0, \ \frac{\partial u}{\partial x}(\ell) = 0$$

Eigenmodes:

$$X_n(x) = \sin \frac{n\pi x}{2\ell}$$

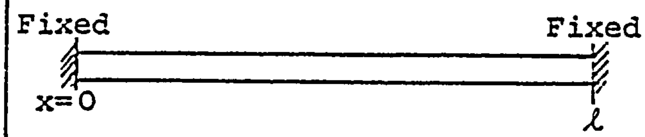
$n = 1,3,5 \ldots$.



Eigenvalues:

$$K_n = \frac{n\pi}{2\ell}$$

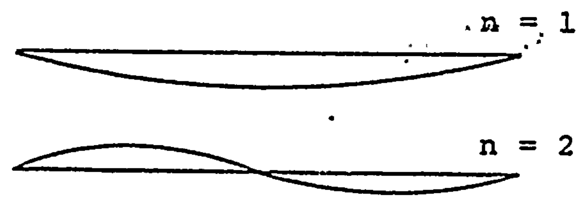
Case 2



$$U(0) = 0, \ U(\ell) = 0$$

$$X_n(x) = \sin \frac{n\pi x}{\ell}$$

$n = 1,2,3 \ldots$.



$$K_n = \frac{n\pi}{\ell}$$

WASHINGTON PUBLIC POWER SUPPLY SYSTEM. NUCLEAR PROJECT NO. 2	EIGENMODES AND EIGENVALUES FOR TWO CASES OF BOUNDARY CONDITIONS	FIGURE A-2

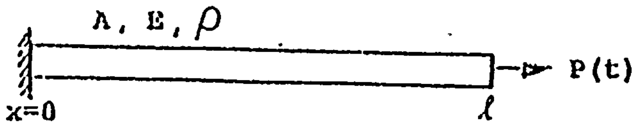
WASHINGTON PUBLIC POWER SUPPLY SYSTEM
NUCLEAR PROJECT NO. 2

VIBRATIONS DUE TO APPLIED FORCE AND IMPOSED MOTION AT FREE END

FIGURE A-3

Problem 1

Applied Force at Free End



$$u(x,t) = \frac{2}{\rho A \ell} \sum_{n=1,3,5..} \frac{(-1)^{\frac{n-1}{2}}}{\omega_n} X_n(x) \Gamma_n(t)$$

where,

$$X_n(x) = \sin \frac{n\pi x}{2\ell}$$

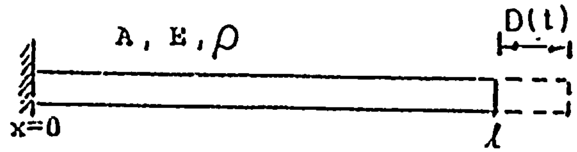
$$\Gamma_n(t) = \int_0^t P(t_1) \sin\omega_n(t-t_1)\, dt_1$$

$$\omega_n = \frac{n\pi a}{2\ell}$$

$$a^2 = E/\rho$$

Problem 2

Imposed Displacememt at Free End



$$u(x,t) = u_1(x,t) + u_2(x,t)$$

$$u_1(x,t) = \frac{x}{\ell} D(t)$$

$$u_2(x,t) = \frac{2a}{\ell} \sum_{n=1,2,3..} \frac{(-1)^n}{\omega_n^2} X_n(x) \Gamma_n(t)$$

where,

$$X_n(x) = \sin \frac{n\pi x}{\ell}$$

$$\Gamma_n(t) = \int_0^t \ddot{D}(t_1) \sin\omega_n(t-t_1)\, dt_1$$

$$\omega_n = \frac{n\pi a}{\ell}$$

$$\ddot{D}(t) = \frac{d^2 D}{dt^2}$$

Note that the response characteristics (x_n; ω_n) of the same bar are different in the above two problems. The series solution of Problem 1 is based on the boundary conditions of Case 1 (Figure A-2). The series part of the solution ($U_2(x \cdot t)$) of Problem 2 is based on the boundary conditions of Case 2 (Figure A-2).