Fred Asiri

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Contract PP150969
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4 December, 1995

Mr. Fred Asiri
Technical Representative
Caltech -- LIGO Project
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Mail Stop 102-33
Pasadena, CA 91125

Subject: LIGO Technical Foundation Analyses

Dear Fred,

The attached report is by Paul MacCalden in response to information requested by Rai Weiss. We are transmitting the following items to you:

Item	Copies	Original	Dated	Description
1	2		12/4/95	LIGO Technical Foundation Analyses

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Very truly yours,

Jeff Hermann, PE
System Engineering Manager

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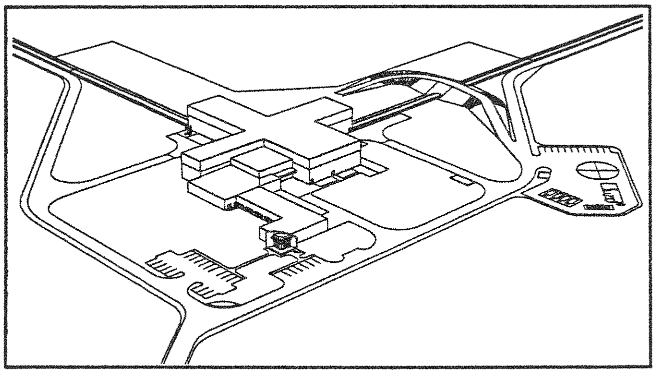


Civil Construction

LIGO Technical Foundation Analyses

Executive Summary and Discussions

December 4, 1995

LIGO
Laser Interferometer Gravitational-Wave Observatory
California Institute of Technology
The Ralph M. Parsons Company
Contract Number: PP150969

LIGO Document ______

Appendix

1. Executive Summary

The vibration analyses presented in this report have been conducted using the baseline foundation thickness of 68-inches for the technical foundations. This baseline thickness was developed from the conceptual studies that assumed that the technical foundations would be located in clean rooms.

The assumed clean rooms were designed with low velocity return air ducts in the technical foundation. Space for nominal four foot diameter return air ducts, reinforcing steel, buried conduit and utilities in the foundation slab led to an 80-inch thickness requirement for the technical foundations. The conceptual design studies indicated that locating the return air ducts in the foundation slab was a cost effective configuration and would increase the foundation stiffness and mass resulting in decreased vibration levels.

At the end of the conceptual design studies it was determined that it was not necessary to provide the rapid number of air changes (15 air changes per hour) for clean rooms for the scientific equipment located on the technical foundations. Thus the 68-inch thick foundation used as a baseline for the design was arrived at as a foundation that would cost about the same as the hollow 80-inch thick foundation.

1.1 Ambient PSD Vibration Analyses

The ambient PSD vibration analyses showed that the vibration levels on the technical foundations would not exceed two times the ambient PSD spectra for any of the technical foundation thicknesses studied. The technical foundation thicknesses studied included 18-inch, 36-inch, and 68-inch foundation slabs. Since the required broad-band responses were no more than twice the ambient PSD spectra these predicted vibration levels are well below the criteria requirement of not exceeding four times the ambient PSD spectra. Note the broad-band ambient vibration criteria states that the foundations shall not exceed twice the ambient displacement spectra (meters/square-root-Hertz) or in terms of PSD spectra the broad-band ambient vibration criteria shall not exceed four times the ambient PSD spectra (meters-squared/Hertz). The difference in the two criteria statements is that the displacement criteria spectra are the square root of the PSD spectra. Also note that either of these spectra can be shown as acceleration/square-root-Hertz or as acceleration-squared/Hertz, respectively.

1.2 Acoustically Induced Vibration Analyses

The acoustic induced vibration analyses used the LIGO acoustic criteria and an estimate made by Dr. Marshall Long of the expected acoustic pressure levels acting on the LVEA technical foundation. These acoustic pressure spectra were input directly into finite element models of the technical foundations using the STARDYNE computer code and the responses of the finite element models are shown as vibration PSD spectra on the foundation surface.

The results of the acoustic analyses indicated that the acoustic induced vibrations of an 18-inch thick foundation would exceed the vibration criteria which has a limit of one times the ambient

PSD spectra. The 36-inch thick foundation would meet the vibration criteria with essentially no margin of safety. The 68-inch thick foundation would satisfy the PSD vibration criteria for acoustic inputs by a factor of about 10 or by a factor of about 3 for the displacement vibration spectra which is equal to the square-root of the PSD spectra.

1.3 Thermally Induced Deformations

Thermally induced deformations were based on air temperature changes at a rate of 2 °F per hour. Since the time duration of interest is about ten minutes, this relates to a temperature change of 0.33 °F in ten minutes. The film coefficient for the transfer of heat from air to a solid surface varies from 1 to 4 for convection processes. For these analyses a value of 2 was selected to minimize the transfer of heat from the air into the concrete technical foundation and is consistent with the low air velocities expected in the LVEA.

The thermal analysis of the transient heat transfer from the air to the concrete concluded that after ten minutes the air temperature would increase by 0.33 °F, the concrete surface temperature would increase to 0.28 °F, at one inch below the surface the concrete temperature would increase by 0.10 °F, at two-inches below the concrete surface the temperature would increase by 0.02 °F, and at three inches below the concrete surface no significant change in the concrete temperature would occur.

These temperature changes with respect to the concrete depth were input into a two dimensional finite element model of the technical foundation as it is supported on the soil. The finite element models were varied to include various foundation thicknesses and foundation lengths. The resulting finite element deformation calculations indicated that the edges of the foundations would exceed the desired fifty nano-radian relative rotation over a two meter foundation length. This region of high rotations is defined by a zone that extends inward approximately 30 feet from the edge of the foundation slab.

A building heat load analysis conducted after the PDR indicated that the maximum rate of air temperature change used in this analysis might be high by a factor two. Thus instead of an air temperature change of 0.33 °F in ten minutes, the air temperature may only change 0.16 °F in ten minutes during the solar heating of the building during late morning or cooling of the exterior building surface temperatures in the late afternoon. Based on these modifications to the rate of heating or cooling of the interior air temperatures it could be expected that only the perimeter of the LVEA foundation defined by a 15 foot wide zone around the edge of the foundation would exceed the fifty nano-radian relative rotation criteria over a two meter long foundation length.

Also it should be noted that at other times when the air temperatures are more stable over the technical foundation it is not expected that the foundation will be distorting as rapidly as predicted in these analyses and therefore most of the foundation surface should not experience fifty nano-radian rotations over a ten minute duration.

The reason for selecting a ten minute duration is related to the time required to obtain lock after a laser alignment upset has occurred. During this ten minute time the relative rotations must be less than fifty nano-radians over a two meter foundation length in order to regain lock. Another heat load study was made to determine the effects of clouds or rapid weather changes on the air temperature in the LVEA building. The results of this study indicate that the air temperature can change about 1 °F in 36 minutes. This extreme condition results in air temperature variations similar to the original assumption of two degrees per hour.

1.4 HVAC Equipment Vibration Predictions

The HVAC equipment vibration predictions are based on 5 Hz isolation systems supporting the HVAC fan skids. The analyses are based on the fans operating at 1800 rpm (30 Hz). An unbalanced force equal to 0.1g times the rotor weight of the fans is used to provide an upper bound to the unbalanced vibrations produced by the fan rotors. It is expected that the acceptance level of unbalanced force will be approximately 1/4 of this extreme force. The reason for using this conservative estimate of the forcing function is to allow for normal wear so that excessive maintenance on the fans would not be required. It is expected that an annual maintenance inspection and cleaning of the fans would be sufficient to keep the fans operating within this vibration range.

For the corner station mechanical room, it was assumed that six fans were operating simultaneously and that the unbalanced forces from each fan were in phase. A finite element model of the concrete structure supporting the six fans in the mechanical room was made and a steady-state solution was obtained at the two foot thick concrete foundation supported on soil stiffnesses for the fan support structure.

The results presented at the PDR were revised downwards due to an error in the input of the soil damping values. The large soil damping values were applied to the equipment isolation modes rather than the fundamental building modes. The response analyses for the HVAC concrete fan support building were rerun and the results are included in this report. The maximum vertical responses of the concrete foundation occurred at the corners of the HVAC foundation. The estimates of the displacements at the critical vacuum equipment on the technical foundation were made by attenuating the ground surface vibrations emanating from the fan support foundation to the location of the vacuum equipment. This attenuation between the fan support foundation and the vacuum equipment location was found to be equal to a multiplication factor of 1/4. Thus the estimated LVEA foundation vibration is $1.5X10^{-8}$ m versus a spike criteria amplitude of 1.4×10^{-8} m at 30 Hz. This amplitude estimate did not consider the effect of averaging the fan foundation motions which could reduce the vibrations by a multiplication factor of 1/4 or 1/5. Also this amplitude estimate did not include the reductions associated with moving the relatively rigid and massive LVEA concrete foundation on top of the ground which could also reduce the vibrations by a multiplication factor of 1/4 or 1/5. Thus it was expected that the actual spike amplitude measured on the LVEA foundation slab near any of the critical vacuum components would be less than the spike amplitude defined by the criteria at 30 Hz.

Similar analyses were conducted for the Mid Station and End Station where only one fan operates at a time. There are two fans located at each of these stations but one fan is expected to be on standby. The concrete fan support structure is located in the mechanical rooms at these stations and is similarly separated from the surrounding structure.

The maximum vertical displacements at the corner of the fan foundation slab were calculated using a finite element model of the concrete fan support structure resting on the soil stiffnesses. The maximum foundation responses were attenuated based on the separation distance between the critical vacuum equipment location and the foundation slab. The resulting peak amplitude is 0.42 x 10^{-8} m at the vacuum equipment location relative to the spike amplitude criteria displacement limit of 1.4 x 10^{-8} m.

As noted before for the LVEA foundation, it is expected that the average fan foundation motion is about 1/4 of the peak fan foundation motion and an additional attenuation by a multiplication factor of 1/4 could be expected for the vibration reduction expected for the effect of the ground motion forcing the motion of the technical foundations at the Mid Stations and End Stations. Thus it is expected that the spike amplitude criteria will be satisfied for the HVAC fan vibration sources when all of these effects are considered.

The specifications for balancing the HVAC fans and isolating the fan vibrations will require the fan Fabricators to provide equipment that will have vibrations that are reduced by a multiplication factor of 1/4. If further reductions are needed in the future it will also be possible to upgrade the fan isolation system so that the unbalanced fan forces applied to the fan foundations are reduced. It is not recommended at this time to provide a significantly more sophisticated fan isolation system but the isolation system could be upgraded in the future if desired.

1.5 Chiller Equipment Vibration Predictions

The Chiller equipment vibration predictions are based on either mounting the Chiller equipment directly on the concrete foundation or using a 5 Hz isolation system to support the Chiller equipment skids. The analyses are based on the rotating equipment (two screw type compressors) operating at 3600 rpm (60 Hz). An unbalanced force equal to 0.1g times the rotor weight is used to provide an upper bound to the unbalanced vibrations. It is expected that the acceptance level of unbalanced force will be approximately 1/4 of this extreme force. The reason for using this conservative estimate of the forcing function is to allow for normal wear so that excessive maintenance on the rotating equipment would not be required. It is expected that an annual inspection in conjunction with appropriate maintenance would be sufficient to keep the rotating equipment operating within this vibration range.

The Chiller yards are located approximately 300 feet from the technical foundations at the corner station, mid station, and end station. A hand calculation was made to estimate the Chiller equipment foundation vibration amplitude based on the unbalanced forces and the 5 Hz isolation system. The foundation motions were reduced by estimating the attenuation of the ground surface vibrations emanating from the Chiller yard and traveling the 300 feet to the technical foundation. The resultant ground motion at the technical foundation location is 2.9 x 10^{-9} m at 60 Hz for the screw compressors based on a hard mounted Chiller system having no isolation.

The spike amplitude criteria limits the peak amplitude to 3.0×10^{-9} m at 60 Hz. If a 5 Hz isolation system is used the ground motions expected at the LVEA might be reduced to 2.3×10^{-11} m. at 60 Hz.

At isolation frequency ratios above ten, for example for the operating frequency at 60 Hz divided by the isolation frequency of 5 Hz, there is a possibility of surge vibrations in the isolators that will significantly reduce the effectiveness of the isolation system. The effect of isolator surges could result in ground motions at the LVEA ten times greater than predicted, or about 3.0×10^{-10} m. These amplitude estimates did not include the reductions associated with moving the relatively rigid and massive concrete technical foundations on top of the ground which could reduce the vibrations by a multiplication factor of 1/4 or 1/5.

It is evident that the new Chiller systems implemented after the conceptual design was completed have significantly reduced the vibrations produced by the 60 Hz screw type compressors. Similar analyses were conducted for the Chiller equipment fans and pumps with similar results.

1.6 Foundation Thickness Trade Study

A foundation thickness trade study was made for the technical foundations that considered 68-inch thick foundations, 36-inch thick foundations, and 18-inch thick foundations. The results of the various analyses indicated that the acoustical response of the technical foundations appeared to be critical.

The ambient PSD analyses indicated that the fundamental modes of the foundations would be heavily damped and not exceed two times the ambient PSD spectra with the criteria limit being four times the ambient PSD spectra. This result applies to all of the technical foundation thicknesses studied and for the LVEA and VEA foundation types.

The spike amplitude responses at the technical foundations for wind induced vibrations, HVAC fan induced vibrations, and Chiller equipment induced vibrations were not evaluated in detail as to the effects of foundation thicknesses. However, it is not expected that there is an effect due to foundation thickness that is much larger than the relative mass of the foundations. Thus the 36-inch thick foundation would have approximately twice the spike amplitude of the 68-inch thick foundation and the 18-inch thick foundation would have four times the spike amplitude of the 68-inch thick foundation.

The deformation of the technical foundations based on changes in air temperature indicated that there were some small benefits to a thicker foundation. However, based on the 50 nano-radian curvature over a two meter long foundation length for a ten minute time interval, the region of unacceptable curvature was not significantly different for the various foundation thicknesses. Therefore the most significant analysis results were for the acoustically induced vibrations that showed the 18-inch thick technical foundations were not acceptable, the 36-inch thick foundations satisfied the criteria and the 68-inch thick foundation provided a significant margin of safety.

1.7 Conclusions

The 68-inch thick foundation thickness used as a baseline in these analyses remains as the preferred thickness based on technical considerations since it provides a significant margin of safety. The 36-inch thick foundation appears to meet the criteria but does not provide any margin of safety and given the inexact nature of the vibration calculations there could be significant differences between the predicted vibrations and the actual vibrations measured at the completed facility. The 36-inch thick foundation thickness is being considered for cost reduction reasons for the LVEA, the 68-inch technical foundation thickness for the VEA foundations at the Mid Station and End Station should not be reduced since it is evident that there would not be significant cost savings for these small foundations. Also the End Station technical foundation must withstand the thrust forces produced by the vacuum pressures which means that a thicker End Station foundation would be beneficial.

2. Vibration Criteria

An advance copy of the revised vibration and acoustic criteria was received on November 7, 1995. The broad-band vibration criteria limit for acoustically excited vibrations due to facility operations induced noise such as HVAC systems was that the vibrations be less than the LIGO Standard PSD (LSPSD). The broad-band vibration criteria limit for ground excited vibrations due to ambient and facility transmitted noise such as wind was that the vibrations be less than the four times the LIGO Standard PSD (LSPSD).

The spike amplitudes permitted for single frequency sources of vibration are limited for various frequency ranges. In the frequency range from 0.1 Hz to 1.0 Hz the spike amplitude of the Root-Sum-Square RSS of three axes must be less than $2.4X10^{-7}$ m/sec^2. In the frequency range from 1.0 Hz to 50 Hz the spike amplitude of the RSS of three axes must be less than $5.0X10^{-4}$ m/sec^2. In the frequency range above 50 Hz the RSS of three axes must be less than $3.0X10^{-25}$ $\{f/1\ Hz\}^9$ m, where f is the vibrational frequency.

The acoustic requirements ten feet above the LVEA and VEA foundation slabs are given in the following table.

Mean Frequency	Sound Pressure Level (0 db Ref: $2X10^{-4}$ $dyne/cm^2$)
f> 63 Hz	PNC-50
f= 63 Hz	66 db
f= 31.5 Hz	64 db
f= 16 Hz	61 db
f= 8 Hz	57 Hz
f= 4 Hz	55 db

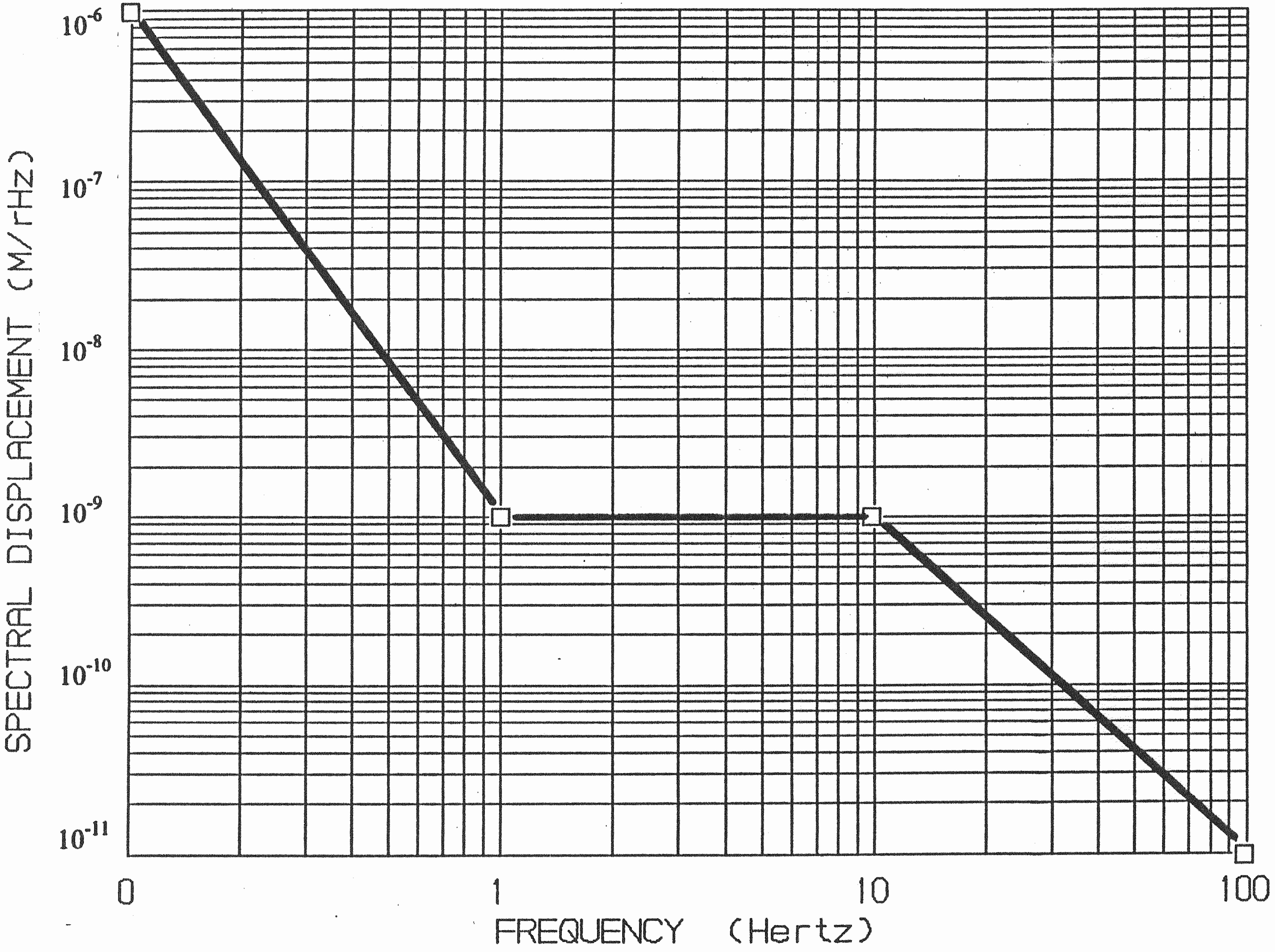
Table 1 -- Acoustic Requirements

The environmental effects require that at least 95 percent of the time, the vibration and acoustic levels must not exceed the limits specified above. This includes the influences of wind, rain, and other local environmental effects.

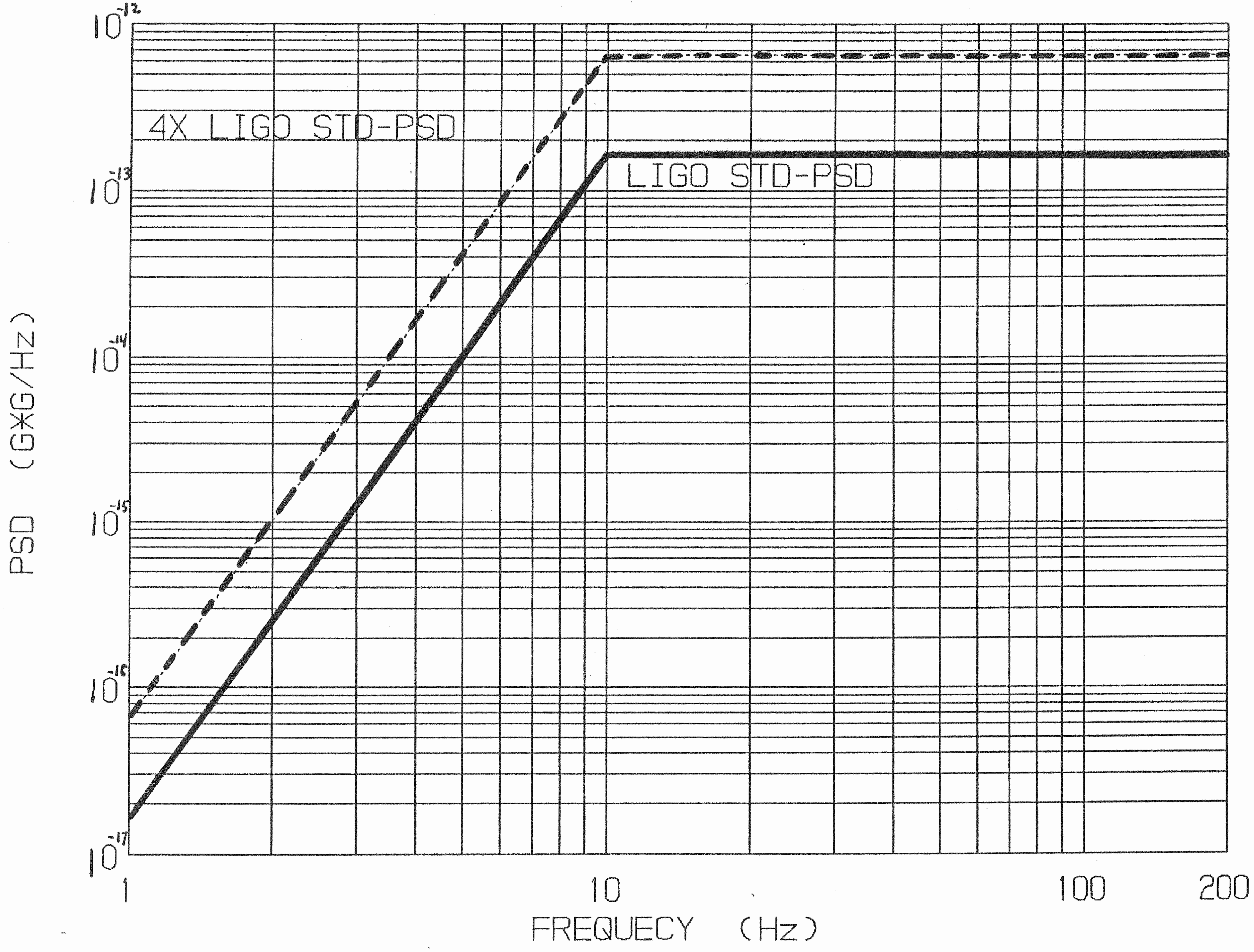
It is noted that Rai Weiss indicated during the PDR that the low frequency spike amplitude criteria was not consistent with earlier versions of the spike amplitude criteria and that it may be required to revise this criteria again for the spike amplitude limits. Also Rai Weiss indicated that an impulsive criteria was needed to limit vibrations produced by extraneous shock loads such as slamming doors, etc. When the revised criteria are transmitted they will be reviewed and incorporated in the design as appropriate.

The LIGO Standard Displacement spectra and the LIGO Standard PSD plots are included at the end of this section along with a copy of the November 7, 1995 vibration criteria.

LIGO STANDARD DISPLACEMENT SPECTRUM



LIGO ACCELERATION PSD CRITERIA



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Laser Interferometer Gravitational Wave Observatory (LIGO) Project

To/Mail Code: A. Lazzarini/ 51-33
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Refer to: LIGO-T950113-03-O
Date: 10/31/95

Subject: Revision of Vibration and Acoustic Requirements for the Laser and Vacuum Equipment Area (LVEA) and Vacuum Equipment Areas (VEA) of the LIGO Facilities

Ref: Vibrational and Acoustic Requirements for the LIGO Facilities, April 12, 1995, LIGO-L950238

A. Broadband Vibration Requirements for the LVEA and VEA Slabs

A1. Definition of the LIGO Standard Power Spectral Density (LSPSD)

$$1\times10^{-18}\left[\frac{f}{\mathrm{Hz}}\right]^{-6}\frac{\mathrm{m}^2}{\mathrm{Hz}};\quad 0.1\mathrm{Hz}\le f\le 1\mathrm{Hz}$$

$$1\times10^{-18}\frac{\mathrm{m}^2}{\mathrm{Hz}};\quad 1\ \mathrm{Hz}\le f\le 10\mathrm{Hz}$$

$$1\times10^{-14}\left[\frac{f}{\mathrm{Hz}}\right]^{-4}\frac{\mathrm{m}^2}{\mathrm{Hz}};\quad f\ge 10\mathrm{Hz}$$

A2. Acoustically-excited vibrations due to “facilities operations-induced noise” (e.g., HVAC systems).

Less than the LSPSD

A3. Ground-excited vibrations due to ambient and facility-transmitted noise (wind, etc.)

Less than four times the LSPSD

B. Narrowband Vibration Requirements for the LVEA and VEA Slabs

B1. 0.1 Hz < f < 1 Hz

The rms acceleration (RSS of three axes, measured along the vertical and two orthogonal horizontal axes) resulting from each narrowband excitation in the frequency band from 0.1 Hz to 1 Hz must be less than 2.4×10^{-7} m/sec^2.

B2. 1 Hz < f < 50 Hz

The rms acceleration (RSS of three axes, measured along the vertical and two orthogonal horizontal axes) resulting from each narrowband excitation in the frequency band from 1 Hz to 50 Hz must be less than 5×10^{-4} m/sec^2.

B3. f > 50 Hz

Above 50 Hz, the allowed rms displacement resulting from each narrowband excitation, x_0 (RSS of three axes, measured along the vertical and two orthogonal horizontal axes) is given by

$$x_0(\mathrm{rms}) = 3\times10^{-25}\left[\frac{f}{\mathrm{Hz}}\right]^9 \mathrm{m}\ .$$

C. Acoustic Requirements Ten Feet Above the LVEA and VEA Slabs

Mean Frequency	Sound Pressure Level (0dB ref: 2 x 10^{-4} dyne/cm^2)
f > 63 Hz	PNC-50
f=63 Hz	66 dB
f=31.5 Hz	64 dB
f=16 Hz	61 dB
f=8 Hz	57 dB
f=4 Hz	55 dB

The units of sound level are given in dB in an octave band around a mean frequency.

D. Environmental Effects

At least 95 percent of the time, the vibration and acoustic levels must not exceed the limits specified in sections A, B, and C above. This includes the influences of wind, rain, and other local environmental effects.

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3. Foundation Configurations

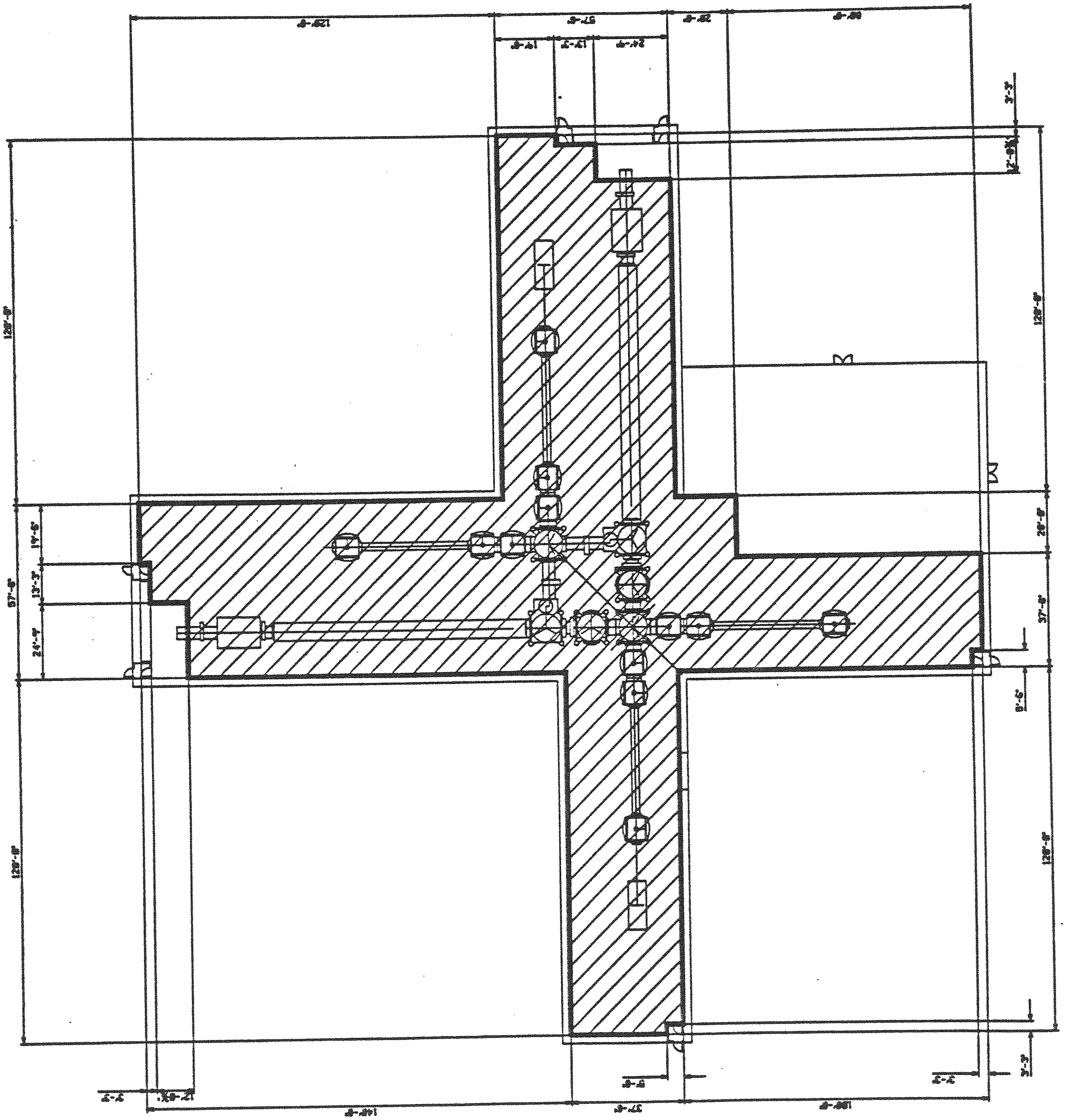
The foundation configurations for the technical foundations are shown on the following three figures for the Corner Station, Mid Station, and End Station. These configurations represent the plan views of the technical foundations studied. There will be 2-inch wide gap around the perimeter of the LVEA and VEA foundations. This gap will be sealed with very flexible material at the top and with a water stop at the bottom which is required for the Livingston site. The location of the vacuum equipment is also shown on these figures.

The LVEA foundation at the corner station is shown on the first figure. The overall dimension of the X-shaped LVEA foundation is about 277 feet by 300 feet with typical floor widths of 37.5 and 57.5 feet.

The Mid Station length is about 77 feet and the width is about 35 feet. The End Station was shown to be 57 feet long at the PDR however, it has been decided to make the Mid and End Stations the same length in order to support future lengthening of the system.

The next two figures describe the development of the concrete fan room at the LVEA. The first figure describes the five fan configuration which was modified to support six fans. The configuration studied in this report was the five fan building configuration with six fans located in the fan building. Later developments resulted in a rectangular fan building to house the six fans. The analysis results obtained for the six fan system located in the slightly smaller fan building should not result in any significant vibration predictions. The last figure describes the two fan building located at the Mid and End Stations. Note that all of the fan buildings are assumed to have a two foot thick reinforced concrete foundation supporting the concrete or concrete block walls and concrete roof of the fan building. This concrete fan building is a standard system that has the benefit of reduced acoustical vibrations as well as providing a platform that isolates the fan building mechanical vibrations from the other facility structures.

8/29/95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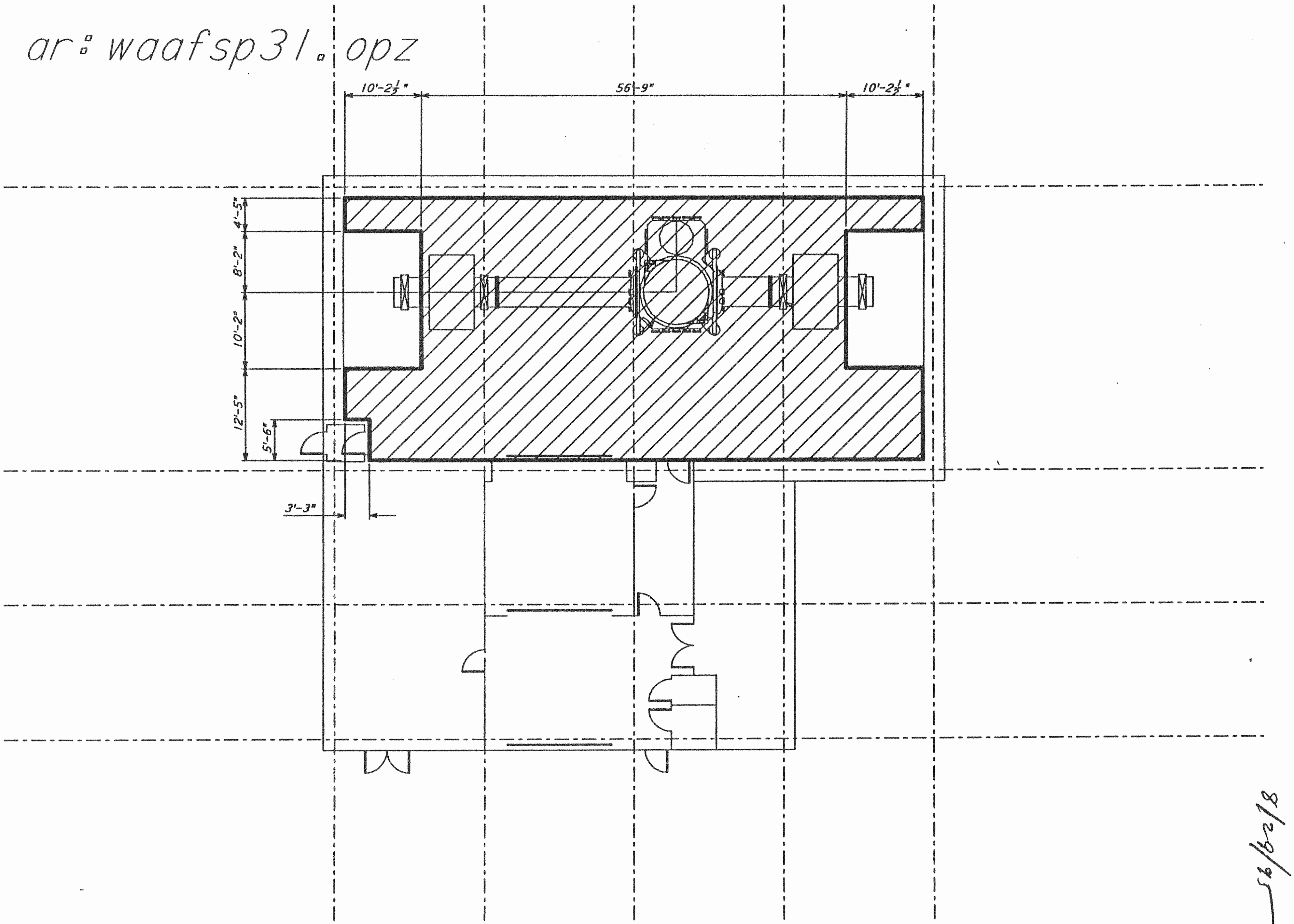

8/29/95

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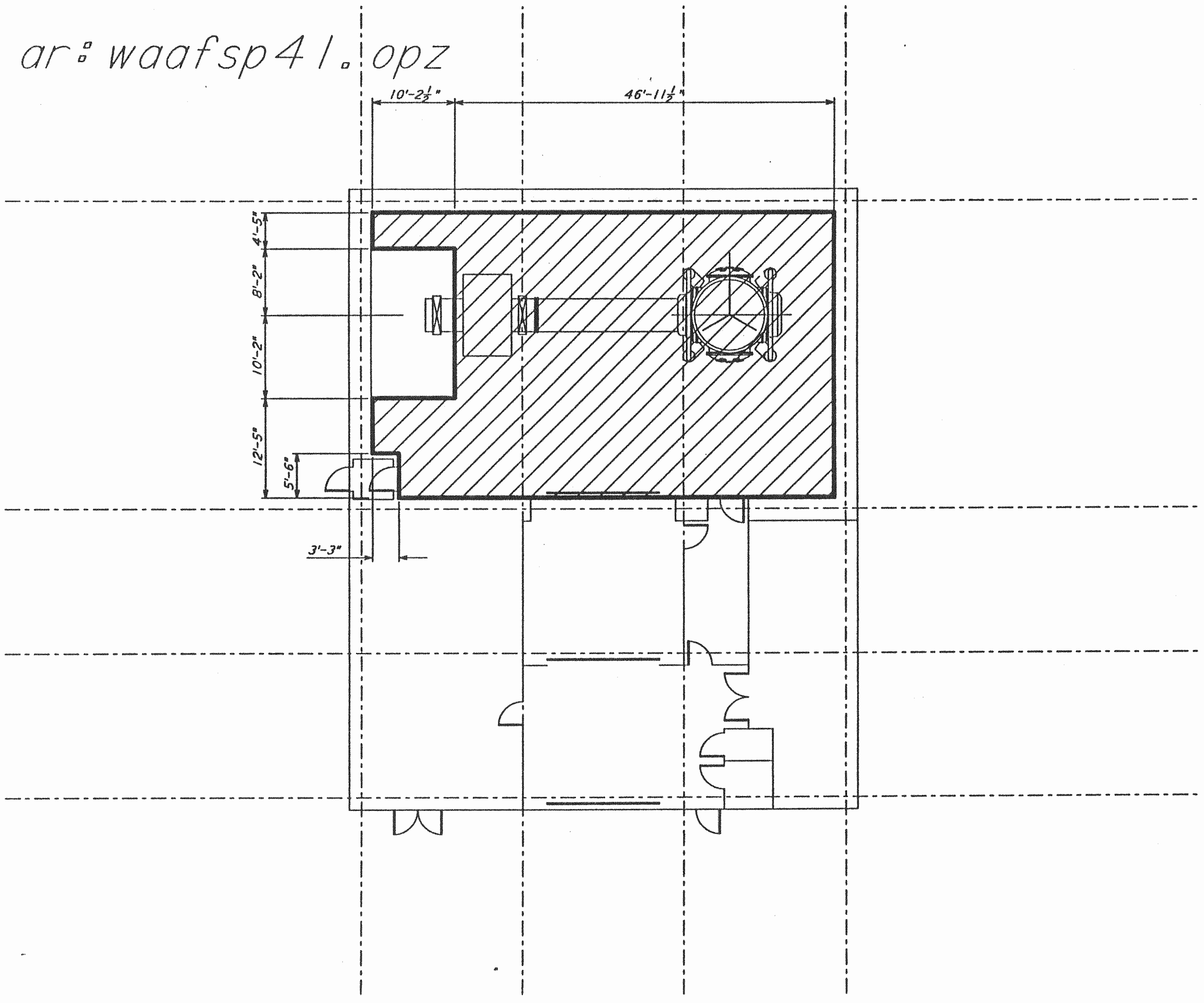

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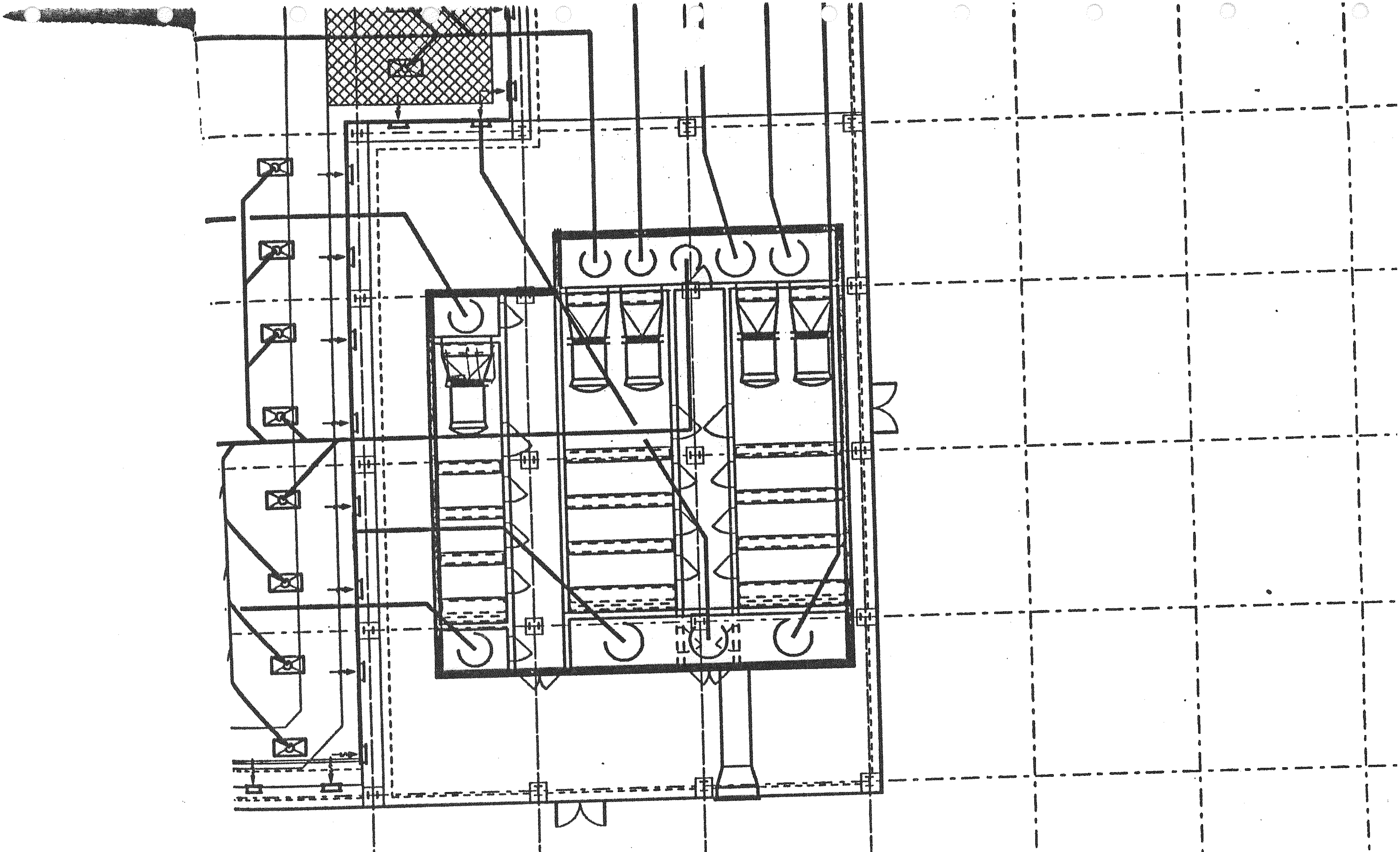
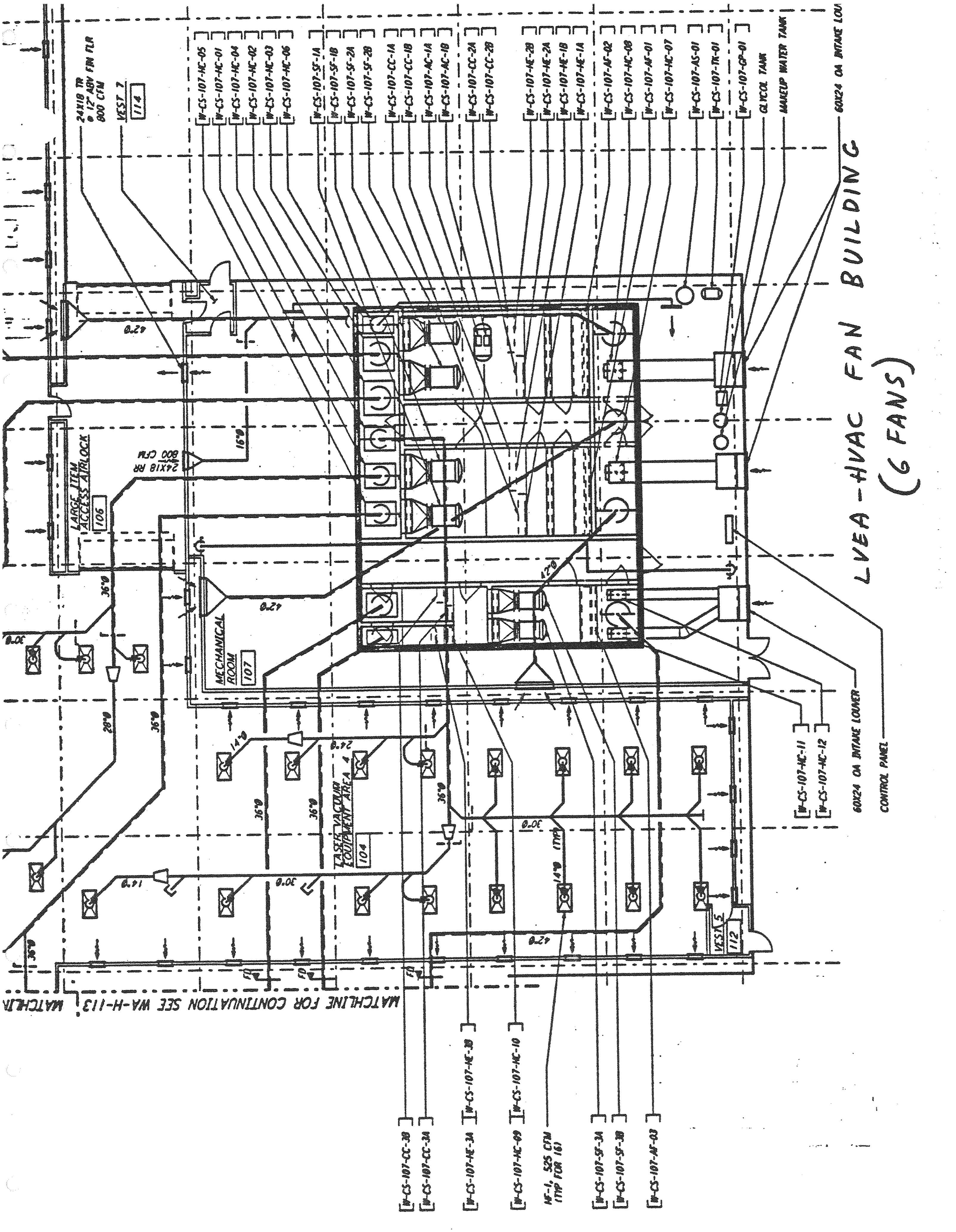
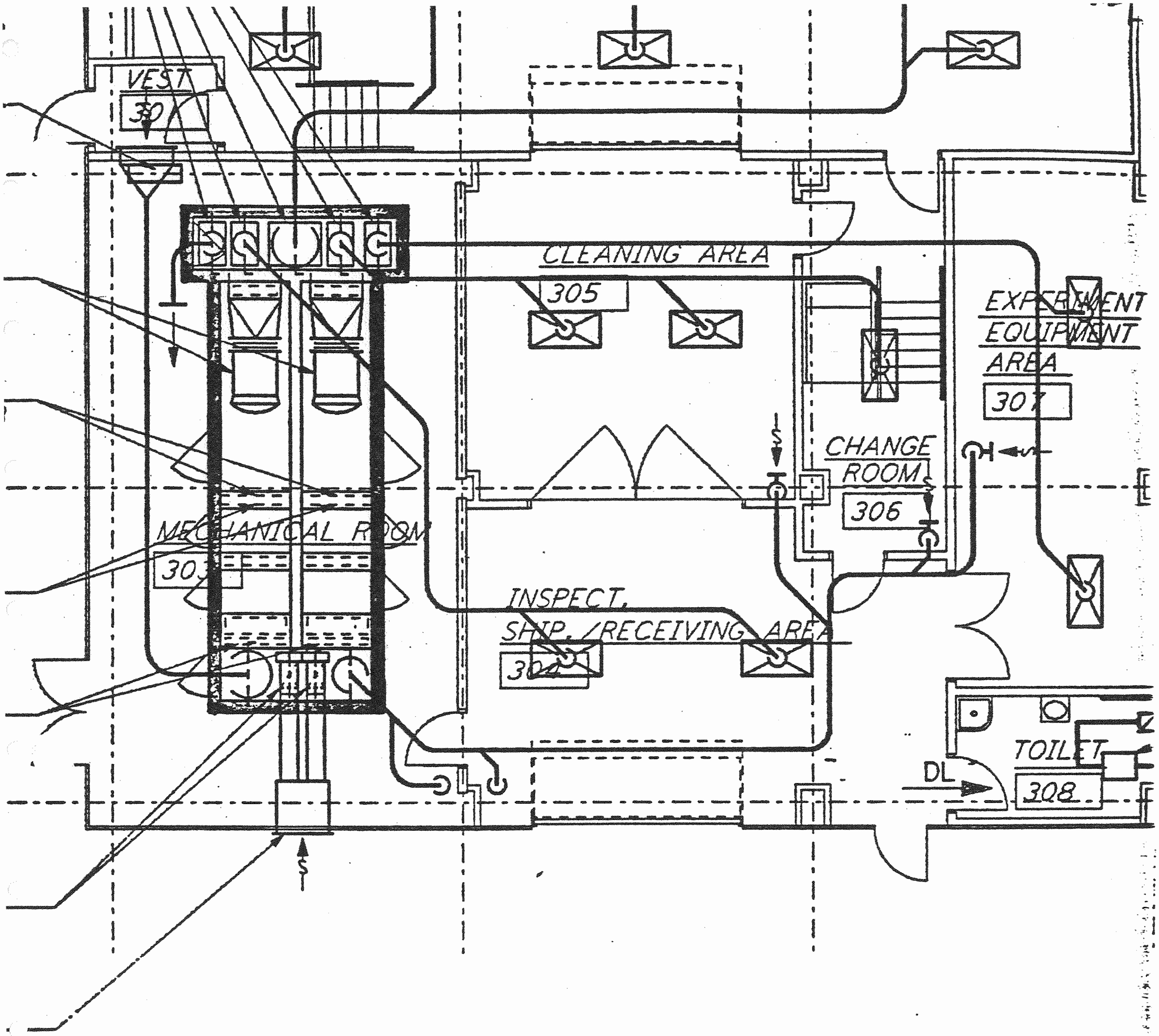


LVEA - HVAC FAN BUILDING
(5 FANS)



LVEA - HVAC FAN BUILDING
(6 FANS)



END STATION "B" FLOOR PLAN

$\frac{1}{8}$" =1'-0"

MID + END STATION FAN BUILDING
(TWO FANS, ONE RUNS)

4. Ambient PSD Induced Vibrations

The ambient PSD vibration analyses showed that the vibration levels on the technical foundations would not exceed two times the ambient PSD spectra for any of the technical foundation thicknesses studied. The technical foundation thicknesses studied included 18-inch, 36-inch, and 68-inch foundation slabs. Since the required broad-band responses were no more than twice the ambient PSD spectra these predicted vibration levels are well below the criteria requirement of not exceeding four times the ambient PSD spectra. Note the broad-band ambient vibration criteria is that the foundations shall not exceed twice the ambient displacement spectra (meters/square-root-Hertz) or in terms of PSD spectra the broad-band ambient vibration criteria shall not exceed four times the ambient PSD spectra (meters-squared/Hertz). The difference in the two criteria statements is that the displacement criteria spectra are the square root of the PSD spectra. Also note that either of these spectra can be shown as acceleration/square-root-Hertz or as acceleration-squared/Hertz.

Finite element models of each of the foundations were made using plate elements for the concrete foundation slab and vertical beams to represent the soil stiffness. These beams were used to represent the vertical and lateral modes of the foundation supported on the soil. In the vertical direction the soil beam properties were based on the ratio of AE/l and the horizontal direction the soil beam properties were based on EI/l^3. The soil properties used in these analyses are representative of the Hanford site. The compressional wave velocity of the soil was estimated to be 1960 feet/second, the shear wave velocity of the soil was estimated to be 890 feet/second, and the soil weight density was estimated to be 105 pounds/cubic feet. These values can also be given as a soil weight density of 105 pounds/cubic feet, a shear modulus of 17,937 psi, and a Poisson's ratio of 0.37. Although all of the calculations have been done using the Hanford soil properties, it does not appear from the results that the somewhat softer soil properties at Livingston would significantly alter the analysis results. The equivalent elastic half-space soil stiffnesses in the vertical and horizontal direction for all of the technical foundations are based on the equations provided in “Vibrations of Soils and Foundations” by F. E. Richart, Jr., J.R. Hall Jr., and R.D. Woods.

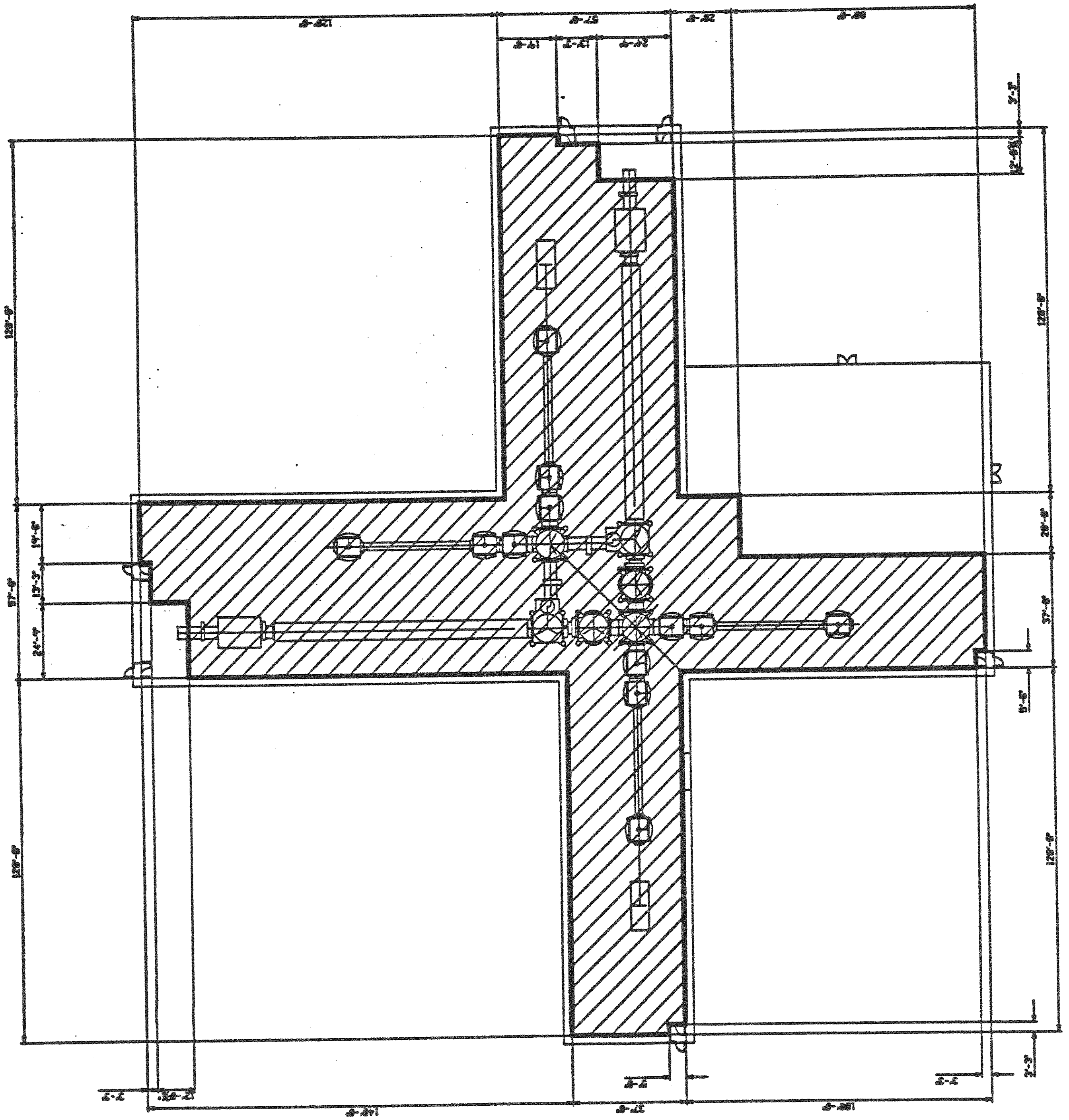
The weight of the reinforced concrete was assumed to be 150 pounds/cubic foot and was modified by the addition of 25% of the 100 pound/square foot live load that is expected to be on the technical foundation floor. This results in an equivalent concrete density of 155 pounds/cubic foot for the 68” thick foundations. The weight of the vacuum equipment components was included in each of the foundation configurations for the modal analyses of the foundations supported on the soil. These component weights are identified as follows; HAM = 22,000 pounds; LASER = 40,000 pounds; LN2 TRAPS = 36,000 pounds; and BEAM SPLITTER = 67,000 pounds. These weights include the isolation stacks as appropriate.

The elastic half-space equivalent damping values were also calculated for the rigid body modes of the technical foundations. In general the vertical modes of vibration for each of the technical foundations have equivalent damping values that are greater than the critical damping ratio. The rigid body rocking damping values were selected as being representative of the minimum soil damping in order to use a conservative value. The values used for the soil damping ratio for each of the 68" thick technical foundations are 98.0%, 54.7%, and 52.0% for the LVEA, Mid Station, and End Station respectively. The concrete material damping was assumed to be equal to 2.0% of the critical damping ratio. The modal damping for each of the foundation modes was computed on the bases of determining the strain energy in the soil material and the strain energy in the concrete material. The STARDYNE computer program then prorated the two material damping values on the bases of the material strain energy ratios. This resulted in the first fundamental modes, around ten Hz, having damping ratios that were dominated by the soil damping values. At higher frequencies, above fifty Hz, the modal damping values were only slightly greater than the 2.0% damping values of the concrete material. For frequencies between ten Hz and 50 Hz there was a gradual transition from high soil damping values to the low concrete material damping value.

The PSD analyses were conducted using the LIGO Standard Spectra (the idealized straight line spectra) applied in all three directions. The results of these analyses indicated that there was very little amplification of the input PSD. The primary amplification occurred at the fundamental frequencies but due to the large damping the amplification was generally less than twice the input PSD. In the high frequency region above 20 Hz to 30 Hz there are significant reductions in the PSD levels computed based on correlated input PSD.

In order to study the effect of using correlated or uncorrelated input PSD spectra additional analyses were made by applying uncorrelated input PSD. In all cases the low frequency modal responses decreased. In almost all cases the high frequency responses also remained low. However, in some cases the very high frequency modes around 100 Hz were amplified significantly. Although all of the modes up to 100 Hz were included in these analyses, the fidelity of such high frequencies modes is questionable given the simplified soil-structure interaction analytical model used. Since the actual correlation functions for the input motion PSD spectra are between the uncorrelated and correlated PSD spectra assumptions it is believed that there will be a significant reduction in the foundation vibrations produced by the ambient PSD ground motions.

The calculations and figures attached to the end of this section are ordered in terms of the Corner Station, Mid Station, and End Station. Typical PSD plots using the correlated input are shown for each of the three foundation thicknesses studied. The computer models, frequencies, modal masses, and the PSD plots for the correlated and uncorrelated inputs ground motions are also included in Appendix A.


128'-8"
37'-6"
14'-6"
13'-3"
24'-9"
3'-3"
128'-8"
28'-8"
37'-6"
128'-8"
3'-3"
148'-8"
37'-6"
3'-3"

PARSONS **Calculation Sheet**	Job Number	Cost Center	Page Number	Sheet of

Rev	Date	By	Ck	Title Soil Properties for Dynamic Analyses

Hanford Soil Properties

Page 7, Soil Report (Upper Layer)

V_p = 1960 ft/sec, Compressional Wave Velocity

V_s = 890 ft/sec, Shear Wave Velocity

Page 14, Soil Report

γ = 105 lb/ft^3, Soil Density

ν = 0.3, Poisson's Ratio

G = 2000 KSF, Shear Modulus

The following consistent soil properties were used in the dynamic analysis.

V_p = 1960 ft/sec

V_s = 890 ft/sec

γ = 105 lb/ft^3

From the elastic media equations

$G = \rho V_s^2$ Page 79, Richart, Hall, + Woods

$$G = \frac{(105)}{(1728)(386.4)} \{890 \times 12\}^2 = 17,937 \text{ psi}$$

PARSONS Calculation Sheet	Job Number	Cost Center	Page Number	Sheet of

Rev	Date	By	Ck	Title Soil Properties For Dynamic Analyses

$$\frac{V_p^2}{V_s^2} = \frac{2(1-\nu)}{1-2\nu} = \frac{(1960)^2}{(890)^2} = 4.85$$

$\nu = 0.37$

Thus for the half-space equivalent soil properties the following values will be used.

$\gamma = 105 \text{ lb/ft}^3 = 6.076 \times 10^{-2} \text{ lb/in}^3$

$G = 17,937 \text{ psi}$

$\nu = 0.37$

PARSONS

Calculation Sheet

	Job Number	Cost Center	Page Number	Sheet of

Rev	Date	By	Ck

Title LVEA
Equivalent Soil Stiffness
Hanford

Soil Properties @ Hanford

$G = 17{,}937$ psi

$\gamma = 105$ lb/ft^3

$\nu = 0.37$

Vertical Soil Stiffness Page 351, Richart, Hall, + Woods

$$K_V = \frac{G}{1-\nu}\beta_z\sqrt{A}$$

$A = 3{,}593{,}827$ in^2

Assume square foundation

$\beta_z = 2.15$ (from graph on page 351)

$$K_V = \frac{(17{,}937)(2.15)\sqrt{3{,}593{,}827}}{(1-0.37)} = 116.04 \times 10^6 \text{ lb/in}$$

Horizontal Soil Stiffness, Page 351, Richart, Hall + Woods

$$K_H = 2(1+\nu)G\beta_x\sqrt{A}$$

$\beta_x = 0.97$ (from graph on page 351)

$$K_H = 2(1.37)(17{,}937)(0.97)\sqrt{3{,}593{,}827} = 90.375 \times 10^6 \text{ lb/in}$$

PARSONS

Calculation Sheet

Job Number	Cost Center	Page Number	Sheet of

Rev	Date	By	Ck	Title
				LVEA Equivalent Soil Stiffness Hanford

There are 2297 soil nodes in the FEM model.

LVEA - PB1.SAP

Vertical Soil Stiffness of Equivalent Soil Beams

$$\delta_V = \frac{P\ell}{AE} \quad , \quad \overline{K}_V = \frac{\overline{A}\,E_e}{\ell} \quad \left\{\text{Axial Deformation of Soil Beam}\right\}$$

$$\overline{K}_V = \frac{K_V}{2297}$$

$$\ell = 68''$$

$$\overline{A} = \frac{A}{2297} = \frac{3,593,827\text{ in}^2}{2297} = 1,565\text{ in}^2$$

Solve for E_e

$$E_e = \frac{\overline{K}_V\,\ell}{\overline{A}} = \frac{(K_V/2297)(68)}{(A/2297)} = \frac{(116.04\times10^6)(68)}{(3.59384\times10^6)} = 2196\text{ psi}$$

Horizontal Soil Stiffness of Equivalent Soil Beams

$$\delta_H = \frac{P\ell^3}{12EI} \quad , \quad \overline{K}_H = \frac{12E_eI}{\ell^3}$$

$$I = \frac{\overline{K}_H\,\ell^3}{12\,E_e} = \frac{(90.375\times10^6)(68)^3}{(2297)(12)(2196)} = 469,462\text{ in}^4$$

PARSONS

Calculation Sheet

Job Number	Cost Center	Page Number	Sheet of

Rev	Date	By	Ck

Title LVEA
Equivalent Concrete Density
Hanford

$A = 3{,}593{,}827\ in^2$

Assume 25% of live load (100 lb/ft²) is permanent equipment that adds mass in the dynamic analysis, then

$$W_e = \left(\frac{3{,}593{,}827}{144}\right)(25\ lb/ft^2) = 623{,}928\ lb$$

Nominal concrete density, including steel reinforcement = 150 lb/ft³, then

$$W_c = (150)\left(\frac{3{,}593{,}827 \times 68}{1728}\right) = 21{,}213{,}562\ lb$$

The equivalent concrete density is

$$\gamma = \frac{W_e + W_c}{Volume} = \frac{(21{,}213{,}562 + 623{,}928)}{\frac{(3{,}593{,}827)(68)}{(1728)}} = 154.41\ lb/ft^3$$

Note if the various laser systems and isolation system weights are included then 818,000 lb should be added.

$$\gamma = \frac{(21{,}213{,}562 + 623{,}928 + 818{,}000)}{\frac{(3{,}593{,}827)(68)}{1728}} = 160.2\ lb/ft^3$$

PARSONS Calculation Sheet	Job Number	Cost Center	Page Number	Sheet of

Rev	Date	By	Ck	Title LVEA Equivalent Damping Hanford

Area = A = 3,593,827 in²

Equivalent circular area

$r_0 = \sqrt{\frac{A}{\pi}} = 1069.6$ in

Vertical Damping Ratio (Page 382, Richart, Hall, & Woods)

$$B_z = \frac{1-\nu}{4} \frac{m}{\rho r_0^3} \quad , \quad D_z = \frac{0.425}{\sqrt{B_z}}$$

$\nu = 0.37$

$$\rho = \frac{(105)}{(1728)(386.4)}$$

$$m = \frac{(160.2)(3,593,827)(68)}{(1728)(386.4)}$$

$$B_z = \frac{(1-0.37)\ \{(160.2)(3,593,827)(68)\}}{(4)\ (105)\ (1069.6)^3} = 0.04799$$

$$D_z = \frac{0.425}{\sqrt{0.04799}} = 1.940$$

PARSONS

Calculation Sheet

Job Number	Cost Center	Page Number	Sheet of

Rev	Date	By	Ck

Title LVEA
Equivalent Damping
Hanford

Horizontal Damping Ratio (Page 382, Richart, Hall & Woods)

$$B_x = \frac{(7-8\nu)\,m}{32(1-\nu)\,\rho\, r_0^3}, \qquad D_x = \frac{0.288}{\sqrt{B_x}}$$

$$B_x = \frac{(7-8\times 0.37)\{(160.2)(3,593,827)(68)\}}{32(1-0.37)(105)(1069.6)^3} = 0.06106$$

$$D_x = \frac{0.288}{\sqrt{0.06106}} = 1.165$$

Rocking Damping Ratio (Page 382, Richart, Hall, & Woods)

$$B_\psi = \frac{3(1-\nu)}{8}\,\frac{I_\psi}{\rho\, r_0^5}, \qquad D_\psi = \frac{0.15}{(1+B_\psi)\sqrt{B_\psi}}$$

$$I_\psi = m\left(\frac{r_0^2}{4} + \frac{h^2}{3}\right),$$ (Page 219, Richart, Hall, & Woods)

$$I_\psi = \frac{(160.2)(3,593,827)(68)}{(1728)(386.4)}\left\{\frac{(1069.6)^2}{4} + \frac{(68)^2}{3}\right\} = 1.686\times 10^{10}$$

$$B_\psi = \frac{3(1-0.37)(1.686\times 10^{10})}{8\left(\frac{105}{(1728)(386.4)}\right)(1069.6)^5} = 0.018093$$

$$D_\psi = \frac{0.15}{(1.018093)\sqrt{0.018093}} = 1.0953$$

PARSONS

Calculation Sheet

Job Number	Cost Center	Page Number	Sheet of

Rev	Date	By	Ck

Title LVEA
Equivalent Damping
Hanford

Torsional Damping Ratio (Page 382, Richart, Hall, & Wood)

$$B_\theta = \frac{I_\theta}{\rho r_o^5}, \quad D_\theta = \frac{0.50}{1+2B_\theta}$$

$$I_\theta = \frac{1}{2} m r_o^2$$

$$B_\theta = \frac{m}{2\rho r_o^3}$$

$$m = \frac{(160.2)(3,593,827)(68)}{(1728)(386.4)}$$

$$\rho = \frac{(105)}{(1728)(386.4)}$$

$$B_\theta = \frac{(160.2)(3,593,827)(68)}{(2)(105)(1069.6)^3} = 0.15235$$

$$D_\theta = \frac{0.50}{1+2(0.15235)} = 0.383$$

PARSONS

Calculation Sheet

	Job Number	Cost Center	Page Number	Sheet of

Rev	Date	By	Ck	Title LVEA Equivalent Damping Hanford

Summary

Vertical Mode $\xi = 1.940$

Horizontal Modes $\xi = 1.665$

Rocking Modes $\xi = 1.095$

Torsional Mode $\xi = 0.383$

PARSONS

Calculation Sheet

Job Number	Cost Center	Page Number	Sheet of

Rev	Date	By	Ck

Title LVEA
Rigid Body Frequencies

Vertical

$$W = \frac{(160.2)(3{,}593{,}827)(68)}{1728} = 22.656 \times 10^6 \ lb$$

$$K_V = 116.04 \times 10^6 \ lb/in$$

$$f_V = \frac{1}{2\pi}\sqrt{\frac{(116.04)(386.4)}{(22.656)}} = 7.08 \ Hz$$

Horizontal

$$W = 22.656 \times 10^6 \ lb$$

$$K_H = 90.375 \times 10^6 \ lb/in$$

$$f_H = \frac{1}{2\pi}\sqrt{\frac{(90.375)(386.4)}{(22.656)}} = 6.25 \ Hz$$

ENG-GE-30 (050492)

PARSONS

Calculation Sheet

Job Number	Cost Center	Page Number	Sheet of

Rev	Date	By	Ck

Title LVEA - Corner Station Area

Area

$$(1650-1200) \times (1440-0) = 648{,}000$$

$$-(66)(39) = -\ 2{,}574$$

$$(1890-1440) \times (960) = 432{,}000$$

$$(2130-1440) \times (1890-960) = 641{,}700$$

$$-(66)(39) = -\ 2{,}574$$

$$(3386.625-2130) \times (1890-1200) = 867{,}071$$

$$(2130-1440) \times (3185.625-1890) = 893{,}981$$

$$(1890-1497) \times (3531-3386.625) = 56{,}739$$

$$(39) \times (1890-1656) = 9{,}126$$

$$(2130-1737) \times (3291-3185.625) = 41{,}412$$

$$(39) \times (2130-1896) = 9{,}126$$

$$\text{Total} = 3{,}593{,}827 \text{ in}^2$$

$$\bar{A} = \frac{A}{N} = \frac{A}{2297} = 1{,}565 \text{ in}^2$$

```
                MODAL EXTRACTION DATA

                                 —MODAL WEIGHTS—
MODE EIGEN  NATURAL          GENERALIZED  MAX TRANSLATION   (GEN. WGT. * PARTI FAC**2)
 NO  (w**2 ) FREQUENCY PERIOD  WEIGHT     NODE-DOF VALUE        X1            X2            X3


 1  1356.39     5.862  0.1706 0.649976E+07    5-2  1.0000 1205077.83748 15930527.78906    6389.97939   12.0
 2  1381.05     5.915  0.1691 0.222483E+08  188-1  1.0000 20722571.82175 1358024.63416    158.56745   12.0
 3  1457.81     6.077  0.1646 0.667389E+07 2324-2  1.0000  163115.64608 4789562.36788   10406.69262   12.0
 4  1716.94     6.595  0.1516 0.226328E+07  212-3  1.0000   79414.25981   16424.73345 7032422.99963   12.0
 5  1878.91     6.899  0.1450 0.821366E+07 1680-3  1.0000   22721.13170     661.59685 8789991.80065   12.0
 6  1993.16     7.105  0.1407 0.348350E+07 1694-3  1.0000    2843.93956   60708.70070  216563.89961   12.0
 7  2027.66     7.167  0.1395 0.246072E+07    7-2  1.0000   20730.20730  110480.73360  269670.10228   12.0
 8  2046.71     7.200  0.1389 0.373386E+07 2153-3  1.0000   37345.96784   12596.39399 1938472.35307   12.0
 9  2130.68     7.346  0.1361 0.184816E+07 1291-3  1.0000   15153.63685   27563.58896 3602493.56917   12.0
10  2250.29     7.550  0.1325 0.183593E+07    9-3  1.0000    6932.22997    1989.89852  172368.04582   12.0
11  2410.57     7.814  0.1280 0.249664E+07  539-3  1.0000      38.48161   29611.11862  111781.53693   12.0
12  2486.18     7.936  0.1260 0.163253E+07 1710-3  1.0000  100839.31416   10778.58090   62634.39913   12.0
13  2668.74     8.222  0.1216 0.165667E+07 2328-3  1.0000   17362.80781   12914.15002  134027.81741   12.0
14  2777.42     8.388  0.1192 0.133401E+07  465-3  1.0000   99655.81836   50342.62195   93665.19254   12.0
15  2896.89     8.566  0.1167 0.236289E+07    9-3  1.0000    4884.54566   39437.93657   47226.28526   12.0
16  2982.64     8.692  0.1150 0.394686E+07 1710-3  1.0000   16016.80512  100448.84621   29775.04736   12.0
17  3041.53     8.777  0.1139 0.193870E+07  393-3  1.0000    2155.05964    4213.75764    8369.73720   12.0
18  3249.97     9.073  0.1102  890245.       10-3  1.0000   13200.08527   83729.38965   64519.40141   12.0
19  3407.37     9.290  0.1076 0.171824E+07 2328-3  1.0000  105964.64035    6213.49169     180.63471   12.0
20  3949.12    10.002  0.1000 0.118736E+07 1291-3  1.0000   10654.27453    2549.45044    3064.98571   12.0
21  4202.45    10.317  0.0969 0.109148E+07  393-3  1.0000    3359.69726    3111.72485    2647.42716   12.0
22  4720.16    10.934  0.0915 0.178810E+07 1710-3  1.0000    2931.26595     498.53283   12054.40175   12.0
23  5656.60    11.970  0.0835 0.119556E+07 2328-3  1.0000      35.01583       1.62556   21639.98945   12.0
24  6615.79    12.945  0.0772 0.114539E+07 1710-3  1.0000       7.76552       5.28694   12250.89029   12.0
25  6741.92    13.068  0.0765 0.123708E+07  465-3  1.0000      78.36092      45.09632    2306.77975   12.0
26  7699.94    13.966  0.0716 0.110039E+07 1654-3  1.0000     643.19151      14.33959       0.00349   12.0
27  8873.29    14.992  0.0667 0.108856E+07    9-3  1.0000     175.18994       5.86589    6235.74467   12.0
28  9869.38    15.811  0.0632 0.401619E+07    9-2  1.0000       1.33621     875.10623      85.58017   12.0
29  10408.3    16.237  0.0616 0.118873E+07 1710-3  1.0000       0.08913     122.82492     540.96867   12.0
30  10921.8    16.633  0.0601 0.208535E+07 1368-3  1.0000      80.07451     594.13981     274.40739   12.0
31  12434.5    17.747  0.0563  924867.     1291-3  1.0000     383.05270       9.71760     243.28526   12.0
32  13836.5    18.721  0.0534 0.156559E+07 1654-3  1.0000      93.62834      47.56149      97.15070   12.0
33  14319.1    19.045  0.0525 0.232869E+07   10-1  1.0000     252.57956     223.95255       0.62472   12.0
34  15057.9    19.530  0.0512 0.360514E+07 1710-2  1.0000     200.99163     430.92564       1.60025   12.0
35  15689.1    19.935  0.0502  840601.     2312-3  1.0000      83.74361     292.63429     385.57062   12.0
36  16459.5    20.419  0.0490  774106.     1710-3  1.0000      23.28711      37.59917    1313.87718   12.0
37  17014.1    20.760  0.0482  747602.     2255-3  1.0000      19.75451       1.22443     359.75738   12.0
38  17377.8    20.981  0.0477 0.181834E+07 1059-3  1.0000     115.35664      76.10759      20.44744   12.0
39  18158.7    21.447  0.0466 0.260839E+07 1291-2  1.0000      23.72158      73.88181       0.11719   12.0
40  19735.2    22.358  0.0447 0.133356E+07 2255-3  1.0000      45.26012       0.00665       0.00281   12.0
41  21289.3    23.222  0.0431 0.401438E+07  465-2  1.0000      78.11157      49.88508       0.02057   12.0
42  21604.7    23.393  0.0427 0.144431E+07    9-3  1.0000     108.11884      18.20596      61.70802   12.0
43  23934.7    24.623  0.0406 0.112561E+07   10-3  1.0000      25.04489       0.00002     106.69575   12.0
44  24953.6    25.141  0.0398 0.136750E+07 1915-3  1.0000       7.60879       8.88748     363.02980   12.0
45  25092.5    25.211  0.0397 0.281924E+07  393-2  1.0000       9.53782      10.07964      39.91563   12.0
46  27650.3    26.465  0.0378  399958.      465-3  1.0000       0.04378       4.61162       0.03302   12.0
47  28221.0    26.737  0.0374 0.166434E+07    1-3  1.0000       0.01458      75.33234      84.78116   12.0
48  30000.3    27.567  0.0363 0.102247E+07 2328-3  1.0000       0.47734       5.35567      28.54797   12.0
49  30783.9    27.924  0.0358  640801.     2255-3  1.0000       1.68906       1.12664       6.67177   12.0
50  36817.9    30.539  0.0327 0.122732E+07 2255-3  1.0000       3.35042      12.73599      11.21059   12.0
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           MODAL EXTRACTION DATA
                                  -MODAL WEIGHTS-
MODE EIGEN  NATURAL          GENERALIZED  MAX TRANSLATION  (GEN. WGT. * PARTI FAC**2)
 NO  (w**2 ) FREQUENCY PERIOD  WEIGHT    NODE-DOF VALUE        X1         X2         X3


 51  39347.3    31.570  0.0317 0.155851E+07 1368-3  1.0000    1.16333    8.10219    9.16787   12.0
 52  42587.4    32.844  0.0304  757316.    1654-3  1.0000   3.48326   19.63169    0.09033   12.0
 53  44963.1    33.748  0.0296 0.725277E+07 1710-1  1.0000    1.40774    0.23181    0.05137   12.0
 54  45142.9    33.815  0.0296 0.101692E+07 2255-3  1.0000    0.09321    6.40792    1.91525   12.0
 55  45502.1    33.950  0.0295 0.514047E+07 1291-2  1.0000    0.00394   14.41296    0.00278   12.0
 56  45620.0    33.994  0.0294  561885.    1654-3  1.0000  36.33655   22.01713    0.06985   12.0
 57  50828.4    35.882  0.0279  976844.    2312-3  1.0000   4.39576    2.49568   33.34827   12.0
 58  52064.0    36.315  0.0275  952411.      9-3  1.0000  0.30643    0.01092    7.05939   12.0
 59  56560.4    37.851  0.0264 0.394832E+07 2328-2  1.0000    1.27470    0.11882    0.00001   12.0
 60  57851.3    38.280  0.0261  817126.    1710-3  1.0000   0.87604    0.73603    0.02316   12.0
 61  61457.3    39.455  0.0253 0.110112E+07   9-3  1.0000    0.92058    4.12642    0.58492   12.0
 62  64340.0    40.370  0.0248 0.143940E+07  539-3  1.0000    0.26560   10.43207    0.05809   12.0
 63  70267.3    42.189  0.0237  620796.    1654-3  1.0000  12.43104    0.63211    9.06718   12.0
 64  71861.8    42.665  0.0234 0.269270E+07 1710-2  1.0000    6.20527    4.66377    0.00097   12.0
 65  73491.9    43.146  0.0232  794948.      9-3  1.0000  4.13364    1.86707    0.04112   12.0
 66  75189.5    43.641  0.0229  620139.     10-3  1.0000  0.00160    0.87244  166.90831   12.0
 67  78963.8    44.723  0.0224 0.100029E+07 1296-3  1.0000    0.21863    0.52150    5.83219   12.0
 68  80111.3    45.047  0.0222  612871.    2328-3  1.0000   6.36656    5.75944    2.86567   12.0
 69  81381.0    45.403  0.0220  421697.    1291-3  1.0000   1.27113    0.01123    7.30604   12.0
 70  86339.9    46.766  0.0214 0.121267E+07 2322-3  1.0000    0.09480    0.64003    0.01479   12.0
 71  88331.0    47.302  0.0211 0.171199E+07 2328-2  1.0000    0.04765   20.44248    0.00007   12.0
 72  94347.0    48.886  0.0205  822777.     393-3  1.0000   3.14676    1.71106   24.82502   12.0
 73  97542.2    49.707  0.0201 0.126838E+07   9-3  1.0000    2.83095   14.09334   10.15741   12.0
 74  99833.1    50.287  0.0199  678739.      9-3  1.0000  5.95858    6.30765    0.05306   12.0
 75  101523.    50.711  0.0197  791483.     10-3  1.0000  14.90295    0.87477    6.00745   12.0
 76  101595.    50.729  0.0197 0.287593E+07 1654-1  1.0000    3.74333    0.00008    0.67013   12.0
 77  105449.    51.682  0.0193  996291.    2152-3  1.0000  13.15389   18.70675    0.16496   12.0
 78  109698.    52.713  0.0190  676541.     434-3  1.0000  0.24290    0.83625    0.67689   12.0
 79  110219.    52.838  0.0189  625832.     465-3  1.0000  6.62727    9.62770    0.31121   12.0
 80  112721.    53.435  0.0187 0.412879E+07 2312-1  1.0000    3.93469    0.96098    0.00487   12.0
 81  113223.    53.553  0.0187 0.114590E+07 2328-3  1.0000    6.08128    1.95365    0.69744   12.0
 82  119065.    54.918  0.0182 0.108689E+07 2034-3  1.0000    0.01201    1.09516    1.95429   12.0
 83  119305.    54.973  0.0182 0.234894E+07 2328-1  1.0000    0.10594    0.99839    0.00016   12.0
 84  120236.    55.187  0.0181 0.121683E+07  452-3  1.0000   2.97928    0.18523    1.56776   12.0
 85  124712.    56.205  0.0178  389327.     393-3  1.0000  1.41833    1.78141    0.77342   12.0
 86  129234.    57.215  0.0175 0.430976E+07 1059-2  1.0000    0.00504    0.80642    0.00023   12.0
 87  134876.    58.450  0.0171  623150.    2255-3  1.0000  0.01331    4.17492    1.17846   12.0
 88  136549.    58.812  0.0170 0.128764E+07 1690-3  1.0000    2.17051    2.77783    0.02460   12.0
 89  138149.    59.155  0.0169  684191.     10-3  1.0000  0.06459    0.78292    0.98890   12.0
 90  142446.    60.068  0.0166  673712.    2312-3  1.0000  0.18633    0.36648    0.09955   12.0
 91  142802.    60.143  0.0166 0.205386E+07 2328-2  1.0000    0.81520    0.34809    0.00004   12.0
 92  152915.    62.237  0.0161 0.101077E+07   9-3  1.0000   1.67097    0.03042    0.48396   12.0
 93  156744.    63.011  0.0159  845778.    1681-3  1.0000  2.07870    0.09254    0.38299   12.0
 94  159385.    63.540  0.0157  830173.      9-3  1.0000  0.00002    0.58971    0.00301   12.0
 95  159985.    63.659  0.0157  799017.    2255-1  1.0000  1.14432    0.40884    0.00003   12.0
 96  166562.    64.954  0.0154 0.286784E+07 2255-1  1.0000    0.09018    0.38403    0.00002   12.0
 97  170409.    65.700  0.0152 0.131462E+07 1710-1  1.0000    0.63322    0.79731    0.00001   12.0
 98  170960.    65.806  0.0152 0.101341E+07 2328-3  1.0000    0.84495    0.16355    0.07021   12.0
 99  173612.    66.315  0.0151  872700.     10-3  1.0000  0.19995    0.00132    0.05562   12.0
100   177309.    67.017  0.0149  960809.   1710-1  1.0000   0.00940    0.49338    0.00037   12.0
```

```
*********************************************************************x

              MODAL EXTRACTION DATA

                                        —MODAL WEIGHTS—
MODE EIGEN  NATURAL          GENERALIZED  MAX TRANSLATION  (GEN. WGT. * PARTI FAC**2)
 NO  (w**2 ) FREQUENCY PERIOD  WEIGHT    NODE-DOF VALUE        X1        X2        X3


101  178038.      67.155  0.0149  708160.     2255-3  1.0000    0.06278   0.47414   0.09553   12.0
102  180324.      67.585  0.0148  799434.     1710-3  1.0000    0.24536   0.00550   0.00244   12.0
103  190114.      69.395  0.0144  738724.      415-3  1.0000   0.12082   0.01265   0.03247   12.0
104  198948.      70.989  0.0141  0.139969E+07 2068-3  1.0000    0.32257   0.01766   0.91124   12.0
105  202201.      71.567  0.0140  0.277339E+07 1710-2  1.0000    0.39085   0.09340   0.00024   12.0
106  203752.      71.841  0.0139  0.101216E+07  393-3  1.0000   0.44682   0.17518   0.11398   12.0
107  208142.      72.611  0.0138  0.132204E+07 1654-2  1.0000    0.02705   0.03005   0.00000   12.0
108  211321.      73.163  0.0137  479773.     2312-3  1.0000    0.04150   0.00361   0.13527   12.0
109  214886.      73.778  0.0136  873738.       10-3  1.0000   0.00204   0.03465   0.07949   12.0
110  217961.      74.303  0.0135  0.275906E+07  393-2  1.0000    0.00007   0.08732   0.00028   12.0
111  222382.      75.053  0.0133  680093.     1059-3  1.0000    0.04027   0.28450   0.41293   12.0
112  224888.      75.475  0.0132  549519.        9-3  1.0000   0.14147   0.12550   0.00494   12.0
113  234933.      77.142  0.0130  0.126804E+07  465-2  1.0000    0.05703   0.06341   0.00001   12.0
114  246158.      78.964  0.0127  0.107974E+07 2328-3  1.0000    0.09264   0.62786   0.37677   12.0
115  247864.      79.237  0.0126  0.128461E+07  457-3  1.0000    0.13084   0.09901   0.65452   12.0
116  257240.      80.722  0.0124  239546.     2312-3  1.0000    0.02228   0.04683   0.76152   12.0
117  260966.      81.304  0.0123  0.267978E+07 2255-1  1.0000    0.00362   0.07825   0.00003   12.0
118  263304.      81.667  0.0122  0.135549E+07 1539-3  1.0000    0.06211   0.02419   0.00141   12.0
119  271831.      82.979  0.0121  740133.        1-3  1.0000   0.22317   0.13994   0.98624   12.0
120  275045.      83.468  0.0120  0.180307E+07    9-1  1.0000   0.00097   0.09835   0.00011   12.0
121  276289.      83.657  0.0120  0.214912E+07   10-1  1.0000   0.00310   0.35244   00.00000  12.0
122  277738.      83.876  0.0119  807203.     2312-3  1.0000    0.01243   0.08882   0.08378   12.0
123  279782.      84.184  0.0119  0.240136E+07 2255-2  1.0000    0.03367   0.06249   0.00007   12.0
124  284226.      84.850  0.0118  485478.     2328-3  1.0000    0.15225   0.26492   0.11289   12.0
125  294995.      86.443  0.0116  0.245232E+07 2086-2  1.0000    0.04716   0.07809   0.00011   12.0
126  297811.      86.854  0.0115  545050.        9-3  1.0000   0.06772   0.02386   0.01994   12.0
127  301436.      87.381  0.0114  0.273496E+07 1654-1  1.0000    0.05028   0.07023   0.00017   12.0
128  306251.      88.076  0.0114  361626.     2312-3  1.0000    0.16491   0.13261   1.46133   12.0
129  311897.      88.884  0.0113  0.197469E+07 1692-1  1.0000    0.09053   0.02950   0.00726   12.0
130  312927.      89.031  0.0112  368350.     1059-3  1.0000    0.04415   00.00000  1.00733   12.0
131  316259.      89.504  0.0112  0.185701E+07 1916-2  1.0000    0.00111   0.04411   0.00003   12.0
132  323951.      90.586  0.0110  848673.     2255-3  1.0000    0.01283   0.00156   0.13928   12.0
133  328077.      91.161  0.0110  0.211250E+07 1654-1  1.0000    0.32293   0.03326   0.00002   12.0
134  329561.      91.367  0.0109  0.121967E+07    1-3  1.0000   0.06207   0.00258   0.08228   12.0
135  335062.      92.126  0.0109  0.188443E+07  465-1  1.0000    0.00406   0.01790   0.00275   12.0
136  335400.      92.173  0.0108  727508.     2328-3  1.0000    0.06290   0.19057   0.63439   12.0
137  343477.      93.276  0.0107  0.228202E+07 1710-2  1.0000    0.04718   0.00071   0.00001   12.0
138  348031.      93.892  0.0107  473581.     1059-3  1.0000    0.06344   0.13241   0.21913   10.9
139  348190.      93.914  0.0106  0.165013E+07 1654-1  1.0000    0.18923   0.00853   0.01487   11.3
140  355535.      94.899  0.0105  796617.     1710-3  1.0000    0.00415   0.12985   0.13182   10.6
141  362720.      95.853  0.0104  0.145863E+07  106-3  1.0000    0.10982   0.12506   0.01371    8.9
142  363137.      95.908  0.0104  0.321120E+07 2255-1  1.0000    0.27836   0.03488   0.00002    9.6
143  366432.      96.342  0.0104  917845.      465-3  1.0000   0.14667   0.00216   0.03621   8.3
144  374098.      97.345  0.0103  0.163545E+07 1797-2  1.0000    0.07082   0.00329   0.01332    8.5
145  374713.      97.425  0.0103  889786.      451-3  1.0000   0.40557   0.00176   1.48656   8.0
146  385395.      98.804  0.0101  0.180948E+07  178-1  1.0000    0.02576   0.04668   00.00000   9.1
147  390362.      99.438  0.0101  0.230052E+07  310-1  1.0000    0.34418   0.09859   0.00000    8.2

          THE FOLLOWING ARE APPROX. EIGENVALUES  FOR WHICH MODES WERE NOT REQUESTED.

148  398013.     100.408                                     6.0
149  401403.     100.835                                     5.8
150  404529.     101.227                                     5.0
151  409224.     101.812                                     5.3
152  422361.     103.434                                     5.8
153  429909.     104.354                                     4.0
```

LVEA FOUNDATION PSD ANALYSES

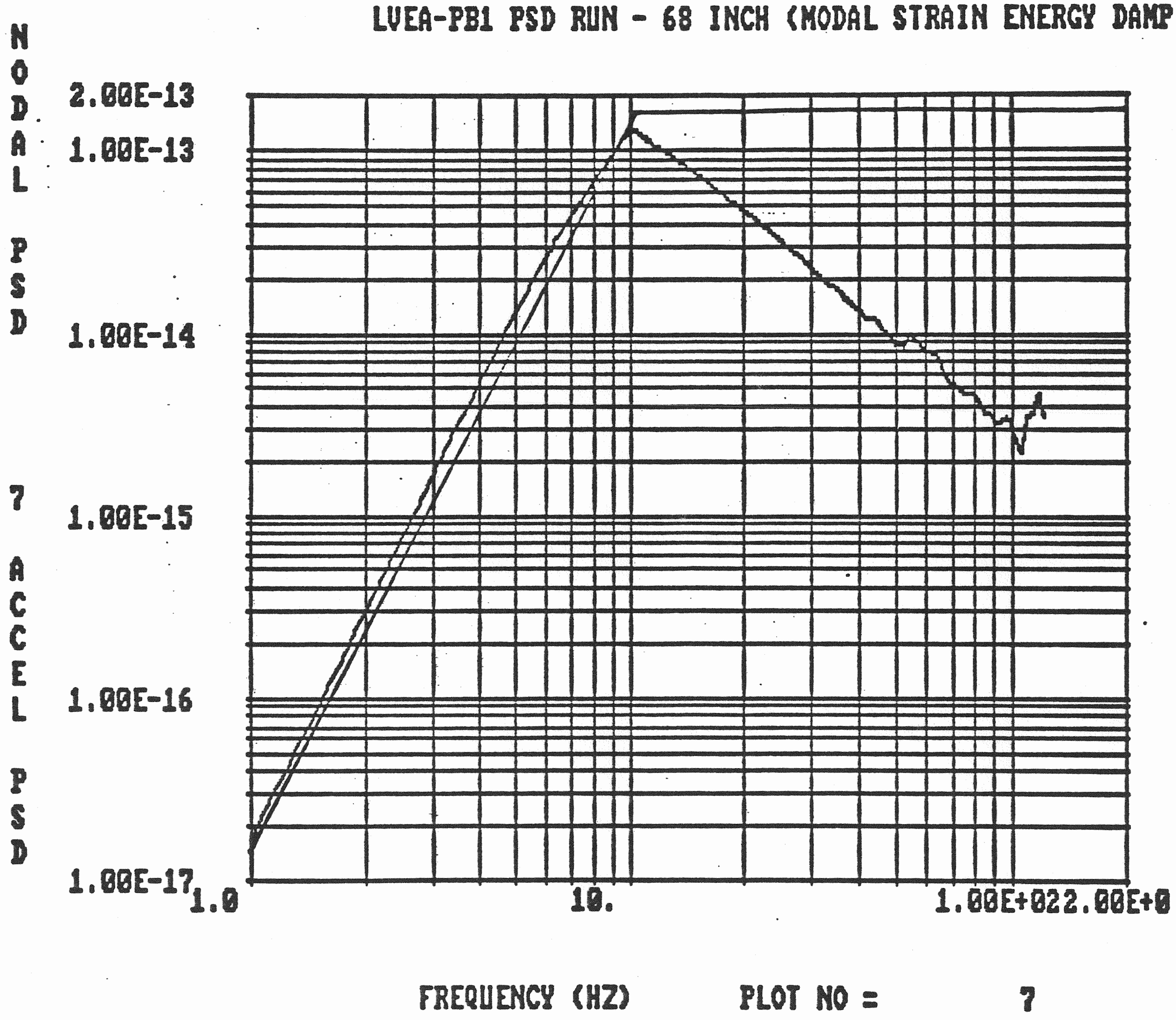
DAMPING FOR SOIL MATERIAL EQUAL TO 98.0% OF CRITICAL

DAMPING FOR CONCRETE MATERIAL EQUAL TO 2.0% OF CRITICAL

MODAL DAMPING CALCULATED IN PROPORTION TO STRAIN ENERGY

Node 792 X1

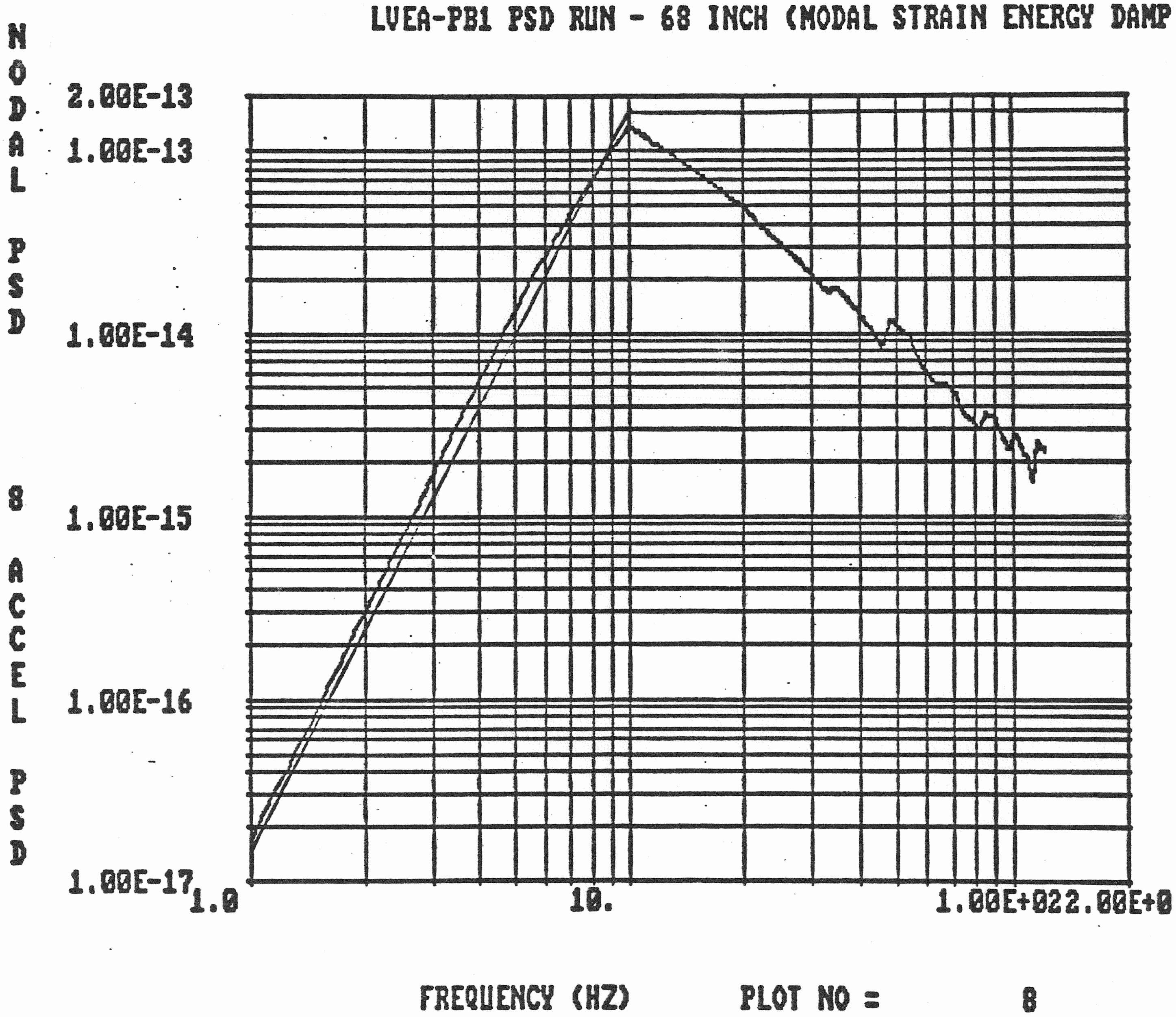
LVEA-PB1 PSD RUN - 68 INCH (MODAL STRAIN ENERGY DAMP

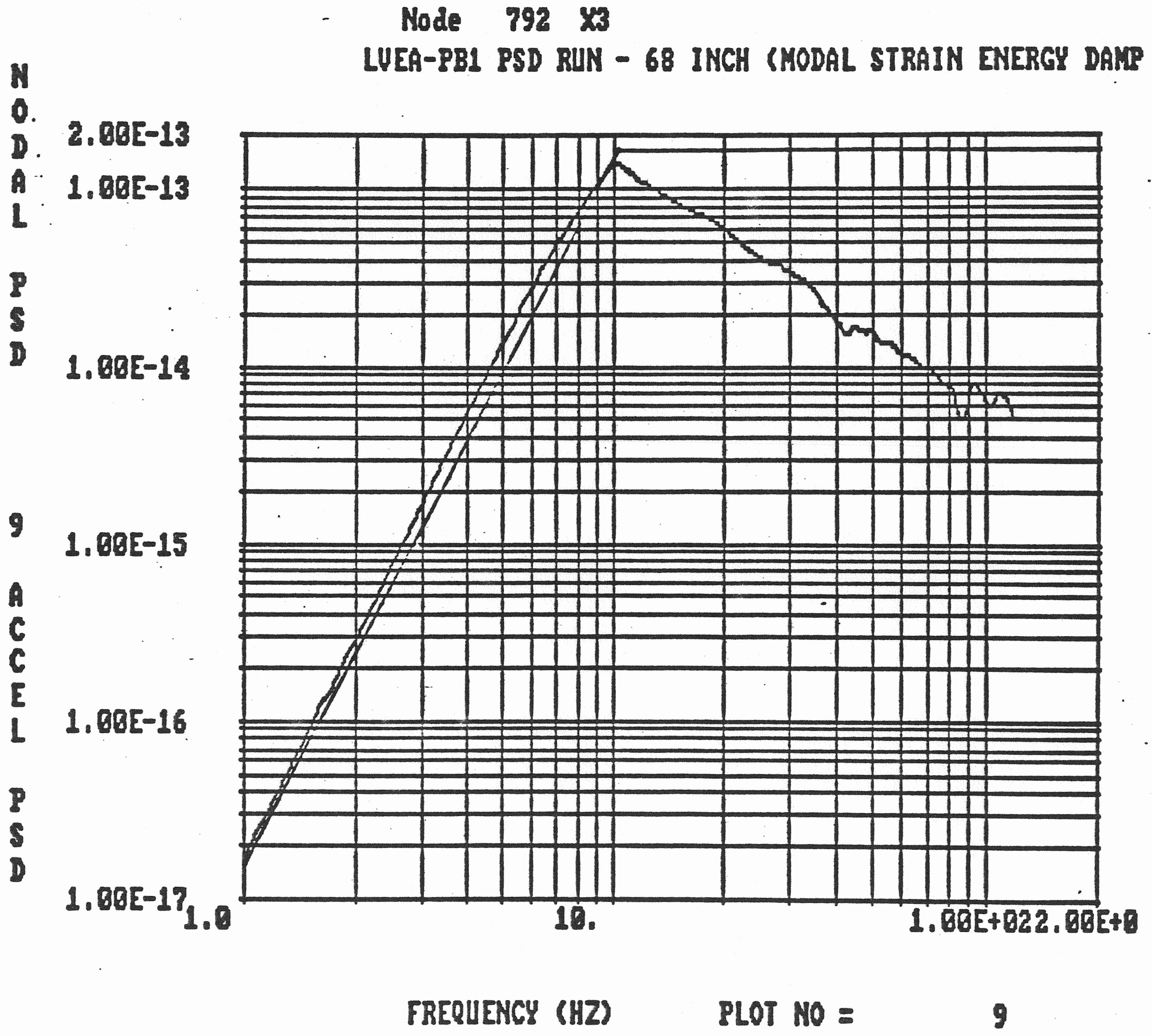


PLOT NO = 7

Node 792 X2

LVEA-PB1 PSD RUN - 68 INCH (MODAL STRAIN ENERGY DAMP



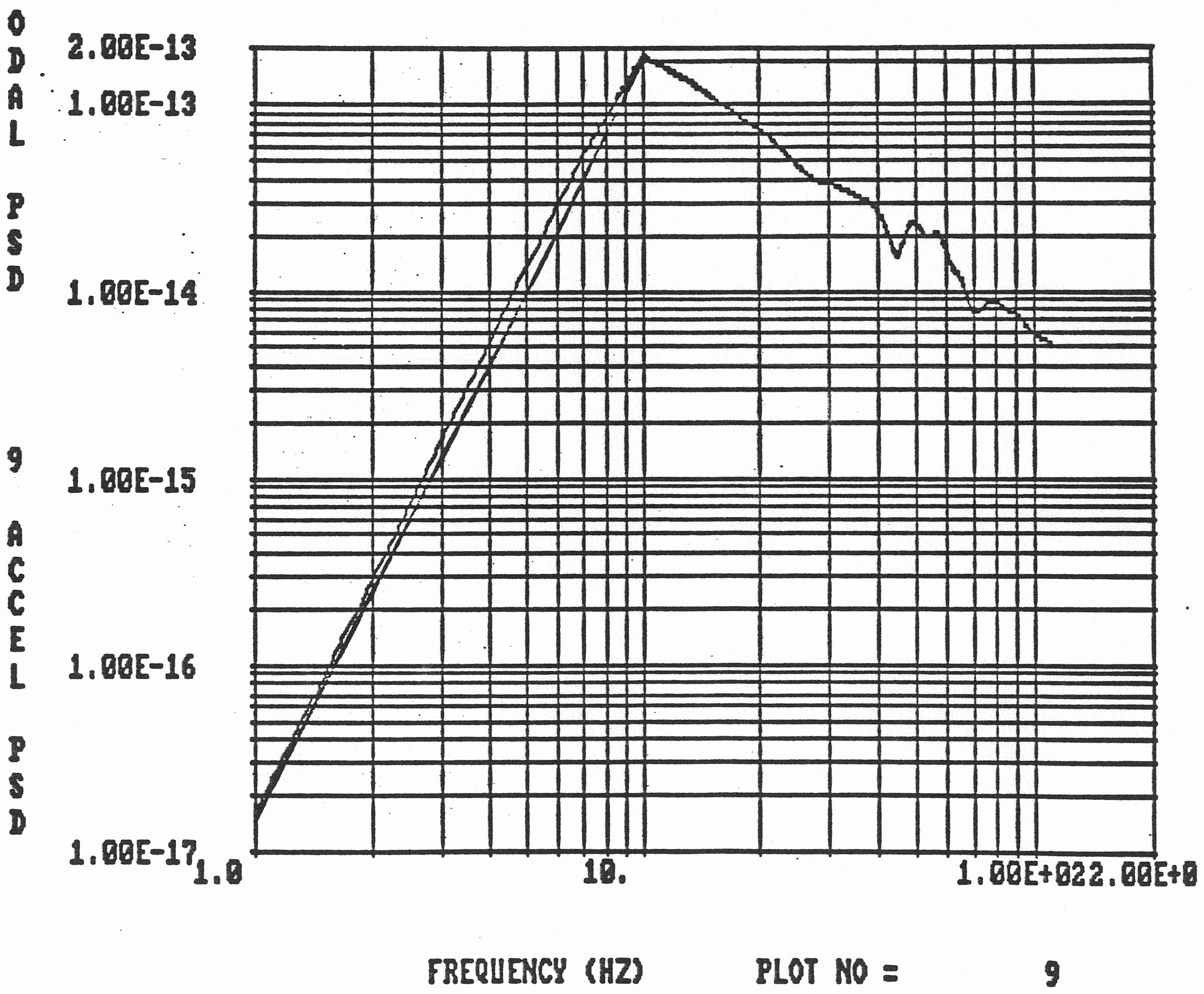


Node 792 X3

LVEA-PB1 PSD RUN - 68 INCH (MODAL STRAIN ENERGY DAMP

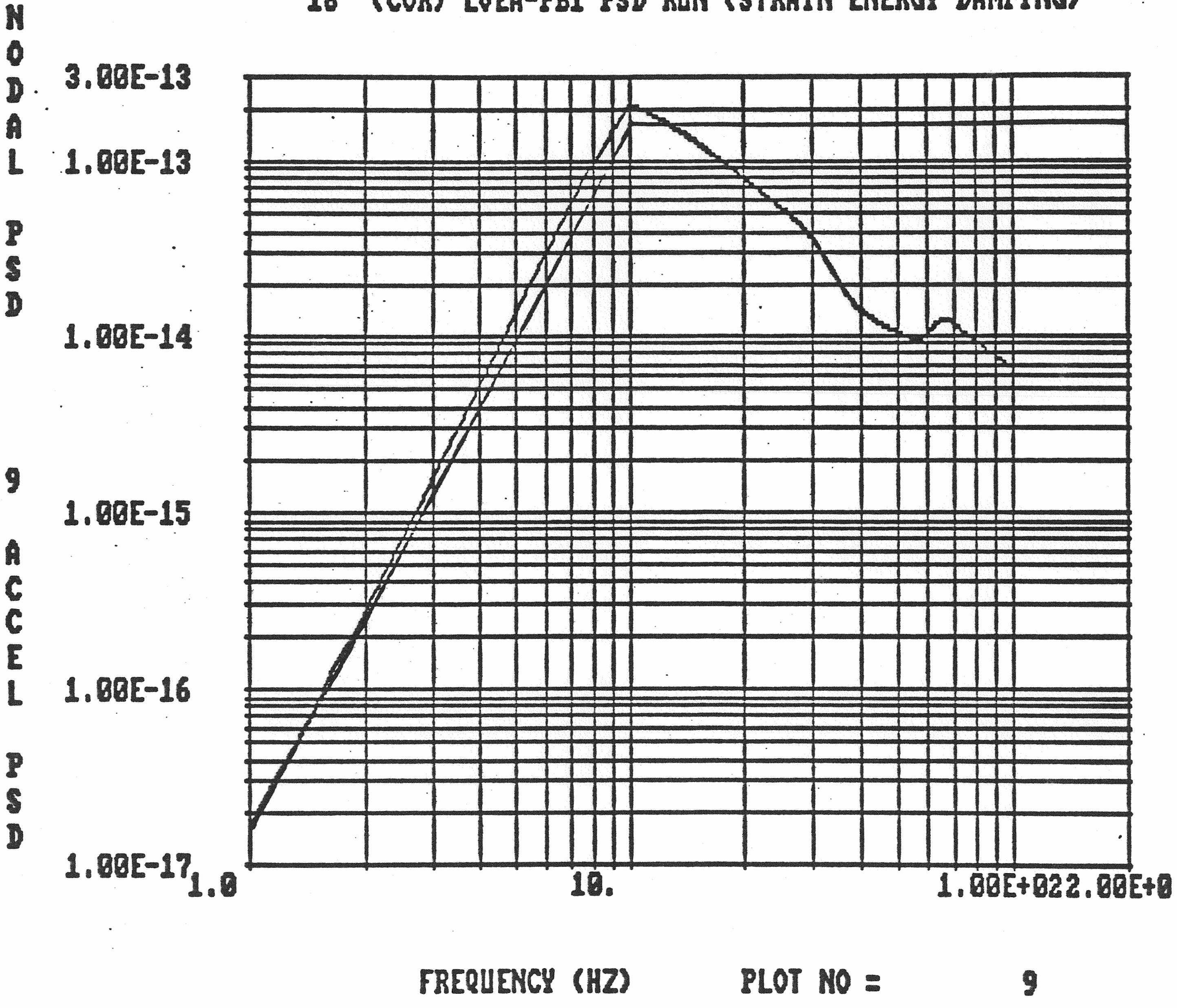
Node 792 X3

LVEA-PB1 PSD RUN-36 INCH (MODAL STRAIN ENERGY DAMPIN



Node 792 X3

18" (COR) LVEA-PB1 PSD RUN (STRAIN ENERGY DAMPING)



PLOT NO = 9

PARSONS

Calculation Sheet

Job Number	Cost Center	Page Number	Sheet of

Rev	Date	By	Ck

Title Mid Station
Equivalent Soil Stiffness
Hanford

Soil Properties - Hanford

$G = 17{,}937$ psi

$\gamma = 105$ lb/ft^3 $= 6.076 \times 10^{-2}$ lb/in^3

$\nu = 0.37$

Vertical Soil Stiffness Page 351, Richart, Hall, + Woods

$$K_V = \frac{G}{1-\nu}\beta_z\sqrt{A}$$

$A = 334{,}298$ in^2

Width = 422 in

Equivalent Length = $\frac{334{,}298}{422} = 792$ in

$\frac{l_e}{w} = \frac{792}{422} = 1{,}877$

$\beta_z = 2.2$ (from graph on page 351)

$$K_V = \left(\frac{17{,}937}{1-0.37}\right)(2.2)\sqrt{334{,}298} = 36{,}215{,}862 \text{ lb/in}$$

Horizontal Soil Stiffness Page 351, Richart, Hall, + Woods

$$K_H = 2(1+\nu)G\beta_x\sqrt{A}$$

$\beta_x = 0.95$ (from graph on page 351)

$$K_H = 2(1+0.37)(17{,}937)(0.95)\sqrt{334{,}298} = 26{,}995{,}468 \text{ lb/in}$$

PARSONS

Calculation Sheet

Job Number	Cost Center	Page Number	Sheet of

Rev	Date	By	Ck

Title Mid Station
Equivalent Soil Stiffness
Hanford

There are 238 soil nodes in the FEM model.

Vertical Soil Stiffness of Equivalent Soil Beams

$\delta_V = \frac{Pl}{AE}$, $\overline{K_V} = \frac{\overline{A} E_e}{l}$ {Axial Deformation of Soil Beams}

$$\overline{K_V} = \frac{K_V}{238}$$

$l = 68$ inches

$$\overline{A} = \frac{A}{238} = \frac{334,298}{238} = 1405 \text{ in}^2$$

Solve for E_e

$$E_e = \frac{\overline{K_V}\, l}{\overline{A}} = \frac{(K_V/238)(68)}{(A/238)} = \frac{(36,215,862)(68)}{(334,298)} = 7367 \text{ psi}$$

Horizontal Soil Beam Stiffness

$\delta_H = \frac{Pl^3}{12EI}$, $\overline{K_H} = \frac{12 E_e I}{l^3}$

$$I = \frac{\overline{K_H}\, l^3}{12\, E_e} = \frac{(26,995,468)(68)^3}{(238)(12)(7367)} = 403,431 \text{ in}^4$$

PARSONS

Calculation Sheet

Job Number	Cost Center	Page Number	Sheet of

Rev	Date	By	Ck

Title Mid Station
Equivalent Concrete Density
Hanford

$A = 334,298 \text{ in}^2$

Assume 25% of 100 lb/ft² live load is permanent equipment; then this equipment weight is:

$$W_e = \left(\frac{334,298}{144}\right)\left(25 \text{ lb/ft}^2\right) = 58,038 \text{ lb}$$

Typical reinforced concrete weight is 150 lb/ft³.

Concrete foundation weight is

$$W_c = (150)\left(\frac{334,298}{144}\right)\left(\frac{68}{12}\right) = 1,973,287 \text{ lb}$$

The equivalent concrete density is

$$\gamma = \frac{W_e + W_c}{\text{Volume}} = \frac{1,973,287 + 58,038}{\frac{334,298 \times 68}{1728}} = 154.41 \text{ lb/ft}^3$$

Note if the beam splitter is added to the foundation weight, then

$$\gamma = \frac{W_e + W_c + 67,000}{\text{Volume}} = 159.50 \text{ lb/ft}^3$$

PARSONS

Calculation Sheet

Job Number	Cost Center	Page Number	Sheet of

Rev	Date	By	Ck

Title Mid Station
Equivalent Damping
Hanford

Area = A = 334,298 in

Equivalent Circular area

$r_0 = \sqrt{\frac{A}{\pi}} = 326.2$ in

Vertical Damping Ratio (Page 382, Richart, Hall, & Woods)

$$B_Z = \frac{1-\nu}{4}\,\frac{m}{\rho r_0^3} \quad , \quad D_Z = \frac{0.425}{\sqrt{B_Z}}$$

$\nu = 0.37$

$$\rho = \frac{(105)}{(1728)(386.4)}$$

$$m = \frac{(159.5)(334{,}298)(68)}{(1728)\;(386.4)}$$

$$B_Z = \frac{(1-0.37)\,\{(159.5)(334{,}298)(68)\}}{(4)(105)(326.2)^3} = 0.1666$$

$$D_Z = \frac{0.425}{\sqrt{B_Z}} = 1.041$$

PARSONS

Calculation Sheet

Job Number	Cost Center	Page Number	Sheet of

Rev	Date	By	Ck	Title
				Mid Station Equivalent Damping

Horizontal Damping Ratio (Page 382, Richart, Hall, + Woods)

$$B_x = \frac{(7-8\nu)\quad m}{32(1-\nu)\quad \rho r_0^3} , \qquad D_x = \frac{0.288}{\sqrt{B_x}}$$

$$B_x = \frac{(7-8\times 0.37)\{(159.5)(334,298)(68)\}}{32(1-0.37)(105)(326.2)^3} = 0.18746$$

$$D_x = 0.665$$

Rocking Damping Ratio {Page 382, Richart, Hall, + Woods}

$$B_\psi = \frac{3\{1-\nu\}}{8}\frac{I_\psi}{\rho r_0^5} , \qquad D_\psi = \frac{0.15}{(1+B_\psi)\sqrt{B_\psi}}$$

$$I_\psi = m\left(\frac{r_0^2}{4}+\frac{h^2}{3}\right)$$ (Page 219, Richart, Hall, + Woods)

$$I_\psi = m\left[\frac{(326.2)^2}{4}+\frac{(68)^2}{3}\right] = 28,143\ m$$

$$m = \frac{(159.5)(334,298)(68)}{(1728)(386.4)}$$

$$B_\psi = \frac{3(1-0.37)\{(159.5)(334,298)(68)\}(28,143)}{(8)(105)(326.2)^5} = 0.0661$$

$$D_\psi = \frac{0.15}{\sqrt{0.0661}\,(1.0661)} = 0.547$$

PARSONS

Calculation Sheet

Job Number	Cost Center	Page Number	Sheet of

Rev	Date	By	Ck

Title Mid Station
Equivalent Damping
Hanford

Torsional Damping Ratio (Page 382, Richart, Hall, & Woods)

$$B_\theta = \frac{I_\theta}{\rho r_0^5}, \qquad D_\theta = \frac{0.50}{1+2B_\theta}$$

$$I_\theta = \frac{1}{2} m r_0^2$$

$$m = \frac{(159.5)(334,298)(68)}{(1728)(386.4)}$$

$$\rho = \frac{(105)}{(1728)(386.4)}$$

$$B_\theta = \frac{(159.5)(334,298)(68)}{(2)(105)(326.2)^3} = 0.49743$$

$$D_\theta = \frac{0.50}{1+2(0.49743)} = 0.251$$

PARSONS

Calculation Sheet

Job Number	Cost Center	Page Number	Sheet of

Rev	Date	By	Ck

Title Mid Station
Equivalent Damping

Summary

Vertical Mode $\zeta = 1.041$ ϕ_4

Horizontal Modes $\zeta = 0.665$ $\phi_1 + \phi_2$

Rocking Modes $\zeta = 0.547$ $\phi_5 + \phi_6$

Torsional Mode $\zeta = 0.251$ ϕ_3

PARSONS

Calculation Sheet

Job Number	Cost Center	Page Number	Sheet	of

Rev	Date	By	Ck

Title Mid Station Area

Area

(149 X 122.5) − (39 X 66) = 15,678.5

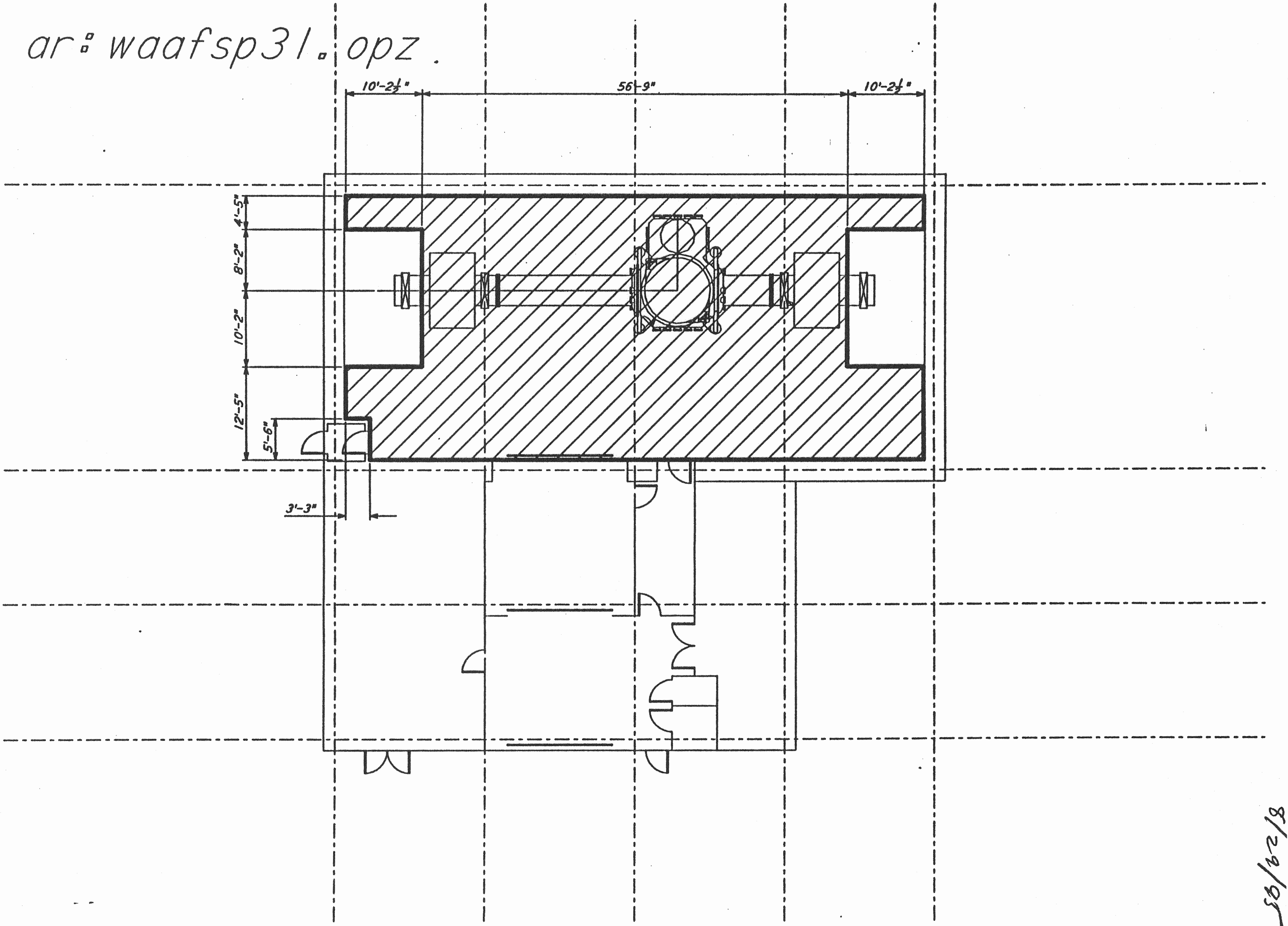
(422 − 369) X (122.5) = 6,492.5

(803.5 − 122.5) X (422) = 287,382.0

(926 − 803.5) X (149) = 18,252.5

(422 − 369) X (122.5) = 6,492.5

Total = 334,298 in^2



8/29/95

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PRINT OF FREQUENCIES

MODE     CIRCULAR
NUMBER   FREQUENCY   FREQUENCY   PERIOD   TOLERANCE
         (RAD/SEC) (CYCLES/SEC)   (SEC)

  1    0.6681E+02 0.1063E+02 0.9404E-01 0.2037E-15

  2    0.6934E+02 0.1104E+02 0.9061E-01 0.3783E-15

  3    0.7870E+02 0.1253E+02 0.7983E-01 0.4405E-15

  4    0.7905E+02 0.1258E+02 0.7948E-01 0.1455E-15

  5    0.9247E+02 0.1472E+02 0.6795E-01 0.4255E-15

  6    0.9640E+02 0.1534E+02 0.6518E-01 0.7829E-15

  7    0.1266E+03 0.2016E+02 0.4961E-01 0.6805E-15

  8    0.1395E+03 0.2220E+02 0.4504E-01 0.5607E-15

  9    0.2072E+03 0.3297E+02 0.3033E-01 0.1356E-14

 10     0.2242E+03 0.3569E+02 0.2802E-01 0.1447E-14

 11     0.2869E+03 0.4566E+02 0.2190E-01 0.5305E-15

 12     0.2931E+03 0.4665E+02 0.2144E-01 0.6775E-15

 13     0.2961E+03 0.4712E+02 0.2122E-01 0.3320E-14

 14     0.3212E+03 0.5111E+02 0.1956E-01 0.8465E-15

 15     0.3320E+03 0.5283E+02 0.1893E-01 0.9243E-15

 16     0.3613E+03 0.5750E+02 0.1739E-01 0.2007E-14

 17     0.3713E+03 0.5909E+02 0.1692E-01 0.1056E-14

 18     0.4339E+03 0.6906E+02 0.1448E-01 0.1082E-14
```

19	0.4571E+03	0.7275E+02	0.1375E-01	0.1114E-14
20	0.4902E+03	0.7802E+02	0.1282E-01	0.1211E-15
21	0.5306E+03	0.8445E+02	0.1184E-01	0.1174E-12
22	0.5355E+03	0.8522E+02	0.1173E-01	0.2436E-14
23	0.5440E+03	0.8658E+02	0.1155E-01	0.2950E-14
24	0.5571E+03	0.8867E+02	0.1128E-01	0.8698E-11
25	0.6369E+03	0.1014E+03	0.9865E-02	0.1831E-08
26	0.7335E+03	0.1167E+03	0.8566E-02	0.3933E-05
27	0.7454E+03	0.1186E+03	0.8429E-02	0.1249E-07

```
  28    0.7694E+03  0.1225E+03  0.8166E-02  0.1632E-04

  29    0.7870E+03  0.1253E+03  0.7984E-02  0.1429E-08

  30    0.8069E+03  0.1284E+03  0.7787E-02  0.1528E-04


 PRINT OF EIGENVECTORS
```

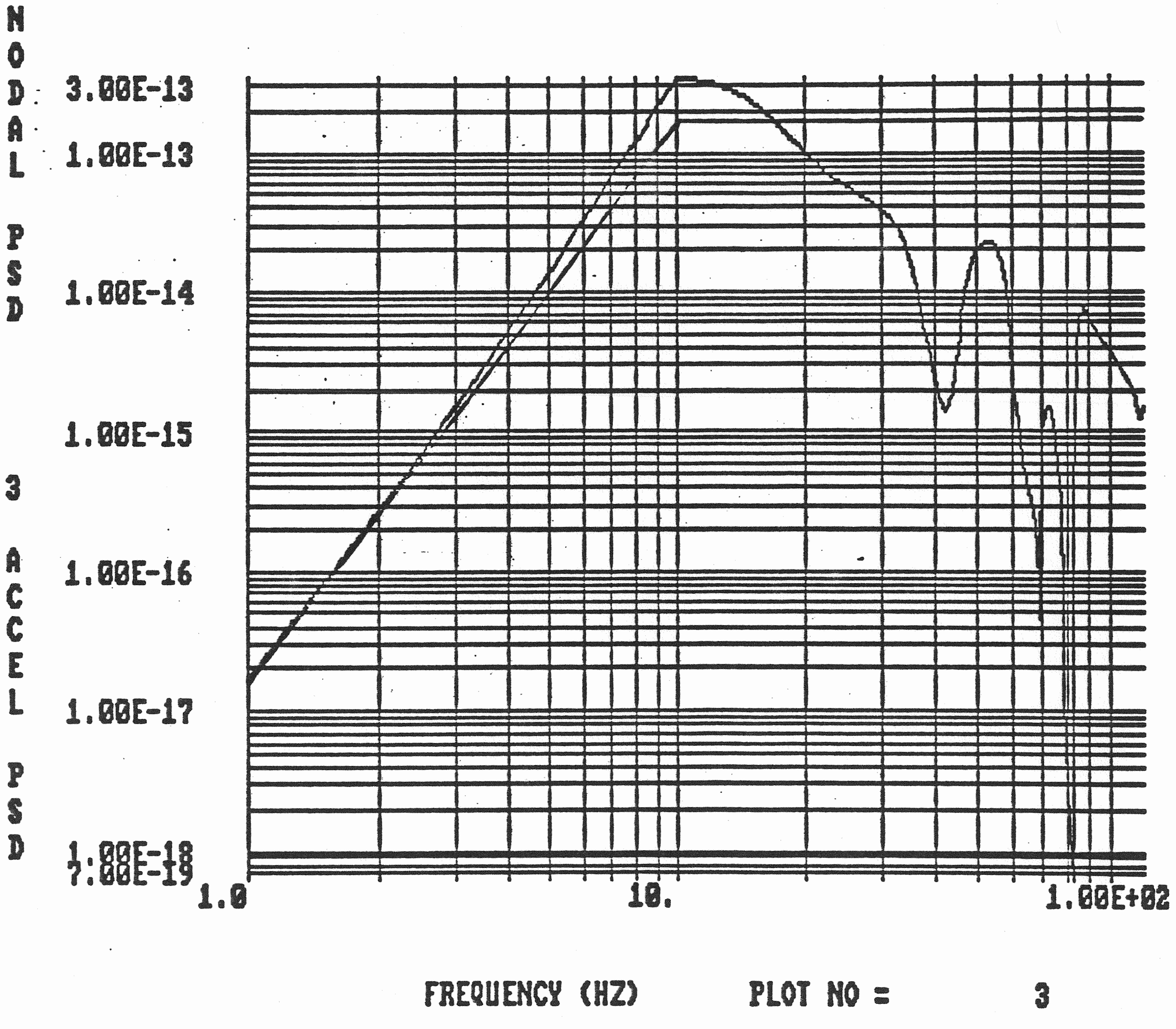
MID-STATION FOUNDATION PSD ANALYSES

DAMPING FOR SOIL MATERIAL EQUAL TO 54.7% OF CRITICAL

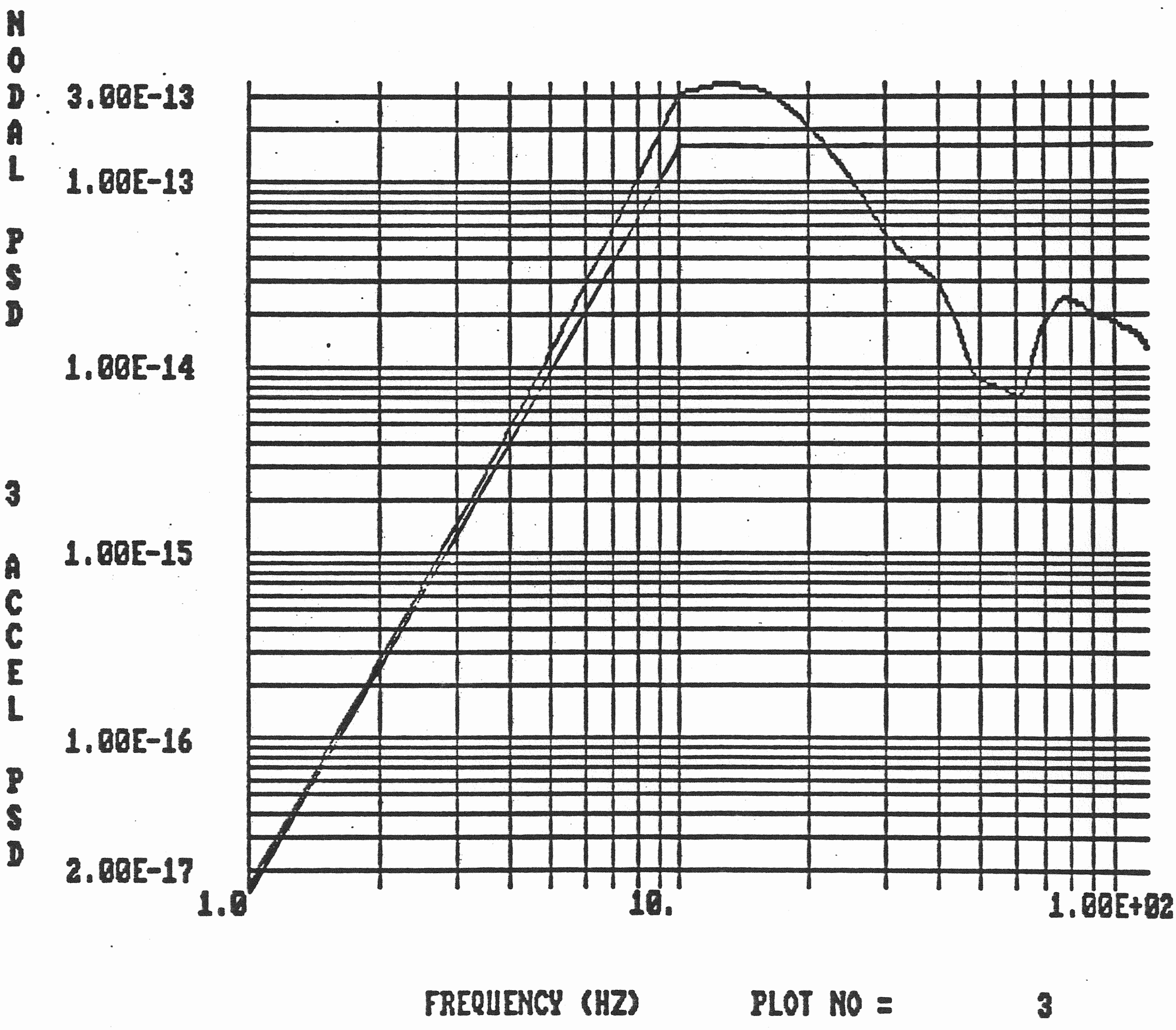
DAMPING FOR CONCRETE MATERIAL EQUAL TO 2.0% OF CRITICAL

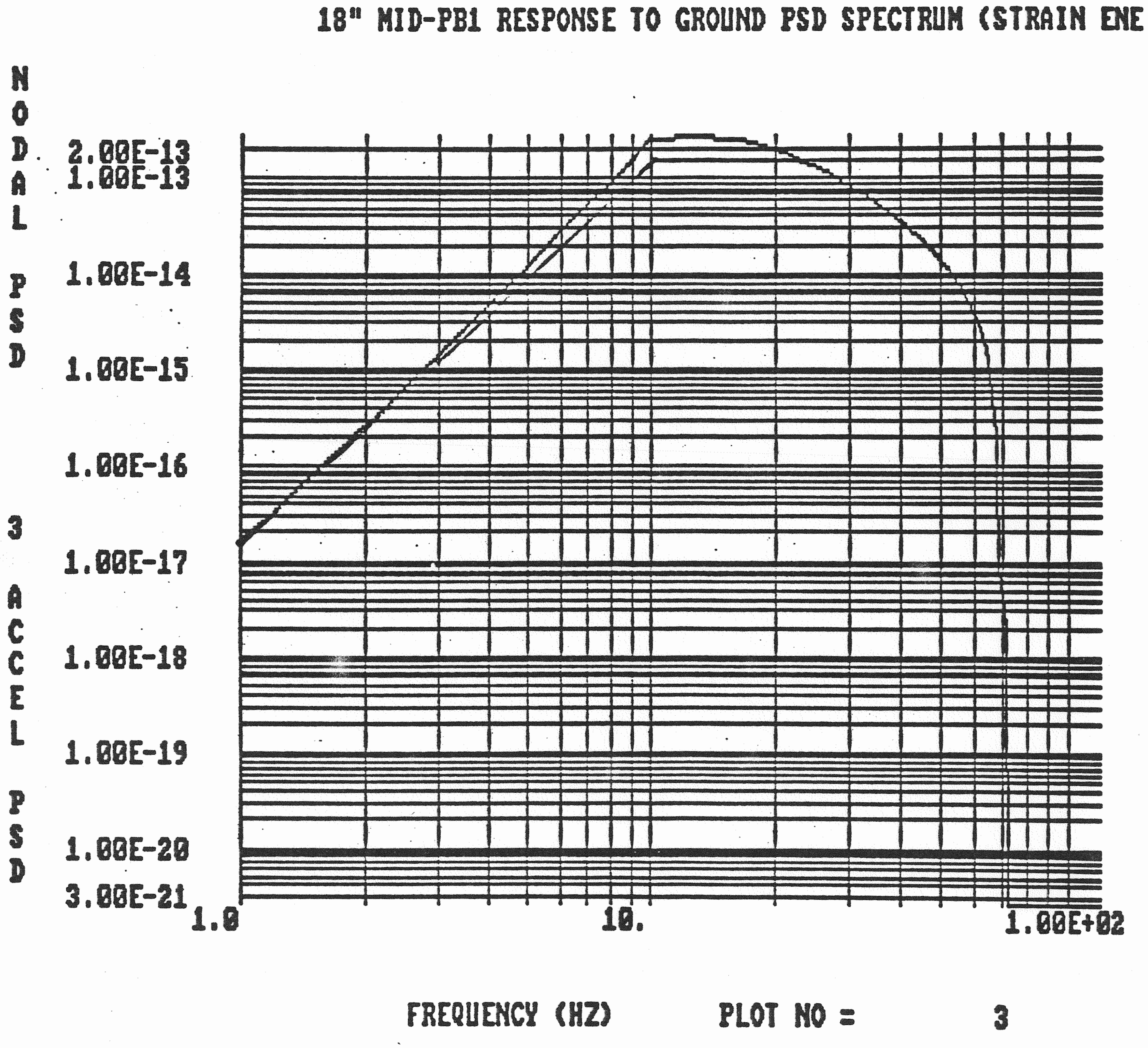
MODAL DAMPING CALCULATED IN PROPORTION TO STRAIN ENERGY

68" MID-PB1 RESPONSE TO GROUND PSD SPECTRUM (STRAIN ENER



36" MID-PB1 RESPONSE TO GROUND PSD SPECTRUM (STRAIN ENE




18" MID-PB1 RESPONSE TO GROUND PSD SPECTRUM (STRAIN ENE
NODAL PSD 3 ACCEL PSD
2.00E-13
1.00E-13
1.00E-14
1.00E-15
1.00E-16
1.00E-17
1.00E-18
1.00E-19
1.00E-20
3.00E-21
1.0
10.
1.00E+02
FREQUENCY (HZ)
PLOT NO = 3

PARSONS

Calculation Sheet

Job Number	Cost Center	Page Number	Sheet of

Rev	Date	By	Ck

Title End Station
Equivalent Soil Stiffnesses
Hanford

Soil Properties @ Hanford

$G = 17{,}937$ psi

$\gamma = 105$ lb/ft^3 $= 6.076 \times 10^{-2}$ lb/in^3

$\nu = 0.37$

Vertical Soil Stiffness Page 351, Richart, Hall, + Woods

$$K_v = \frac{G}{1-\nu}\,\beta_z\sqrt{A}$$

$A = 259{,}968$ in^2 Area

width $= 422$ in

Equivalent length $= l_e = \dfrac{259{,}968}{422} = 616$ in

$$\frac{l_e}{w} = \frac{616}{422} = 1.46$$

$\beta_z = 2.2$ (from graph on page 351)

$$K_v = \left(\frac{17{,}937}{1-0.37}\right)(2.2)\sqrt{259{,}968} = 31{,}936{,}836 \text{ lb/in}$$

Horizontal Soil Stiffness, Page 351, Richart, Hall, + Woods

$$K_H = 2(1+\nu)\,G\,\beta_x\sqrt{A}$$

$\beta_x = 0.95$ (from graph on page 351)

$$K_H = 2(1.37)(0.95)(17{,}937)\sqrt{259{,}968} = 23{,}805{,}862 \text{ lb/in}$$

PARSONS

Calculation Sheet

Job Number	Cost Center	Page Number	Sheet of

Rev	Date	By	Ck

Title End Station
Equivalent Soil Stiffnesses
Hanford

There are 202 nodes in the soil model.
The vertical soil stiffness is:

$$\delta_v = \frac{Pl}{AE} \quad \{\text{Axial Deformation of Soil Beam}\}$$

$$\overline{K}_V = \frac{\overline{A}\,E_e}{l} = \frac{K_V}{202} = \frac{31{,}936{,}836}{202} = 158{,}103 \text{ lb/in/node}$$

$$l = 68 \text{ inches}$$

$$\overline{A} = \frac{A}{202} = \frac{259{,}968}{202} = 1287 \text{ in}^2/\text{node}$$

Solve for E_e

$$E_e = \frac{\overline{K}_V\, l}{\overline{A}} = \frac{(K_V/202)(68)}{(A/202)} = \frac{(31{,}936{,}836)(68)}{(259{,}968)} = 8354 \text{ ps}$$

The horizontal soil stiffness is:

$$\delta_H = \frac{Pl^3}{12EI} \quad \{\text{Fixed-Fixed Bending of Soil Model Beam}\}$$

$$\overline{K}_H = \frac{12\,E_eI}{l^3} = \frac{K_H}{202}$$

Solve for I

$$I = \frac{K_H\, l^3}{(202)(12)(E_e)} = \frac{(23{,}805{,}862)(68)^3}{(202)(12)(8354)} = 369{,}644 \text{ in}^4$$

PARSONS

Calculation Sheet

Job Number	Cost Center	Page Number	Sheet of

Rev	Date	By	Ck

Title End Station
Equivalent Concrete Density
Hanford

$A = 259{,}968 \text{ in}^2$, Area

Assume 25% of 100 lb/ft² live load is permanent equipment, then this equipment weight is

$$W_e = \left(\frac{259{,}968}{144}\right)(25 \text{ lb/ft}^2) = 45{,}133 \text{ lb}$$

Typical reinforced concrete weight density is 150 lb/ft³

The Concrete foundation weight is:

$$W_c = 150\left(\frac{259{,}968}{144}\right)\left(\frac{68}{12}\right) = 1{,}534{,}533 \text{ lb}$$

The modified concrete density is then

$$\gamma = \frac{W_e + W_c}{\text{Vol.}} = \frac{(1{,}534{,}533 + 45{,}133)}{\left(\frac{259{,}968}{144}\right)\left(\frac{68}{12}\right)} = 154.41 \text{ lb/ft}^3$$

Note if the weight of the mirror + isolation stack is added, the equivalent density becomes: (A beamsplitter weighs 67,000 lb)

$$\gamma = \frac{W_e + W_e + 67{,}000}{\text{Vol.}} = \frac{1{,}534{,}533 + 45{,}133 + 67{,}000}{\left(\frac{259{,}968}{144}\right)\left(\frac{68}{12}\right)} = 161 \text{ lb/ft}^3$$

PARSONS

Calculation Sheet

Job Number	Cost Center	Page Number	Sheet of

Rev	Date	By	Ck

Title End Station
Equivalent Damping
Hanford

Area = $A = 259{,}968 \text{ in}^2$

Equivalent Circular Area, radius

$$r_o = \sqrt{\frac{A}{\pi}} = \sqrt{\frac{259{,}968}{\pi}} = 287.7 \text{ in}$$

Vertical Damping Ratio (page 382, Richart, Hall, + Woods)

$$B_z = \frac{(1-\nu)}{4}\frac{m}{\rho r_o^3} \quad , \quad D_z = \frac{0.425}{\sqrt{B_z}}$$

$\nu = 0.37$

$$\rho = \frac{(105)}{(1728)(386.4)} =$$

$$m = \frac{(161 \text{ lb}/\text{ft}^3)\quad(259{,}968)(68)}{(1728)(386.4)} =$$

$$B_z = \frac{(1-0.37)\ \{(161)(259{,}968)(68)\}}{(4)(105)(287.7)^3} = 0.1793$$

$$D_z = \frac{0.425}{\sqrt{0.1793}} = 1.004$$

PARSONS

Calculation Sheet

Job Number	Cost Center	Page Number	Sheet of

Rev	Date	By	Ck	Title
				End Station Equivalent Damping Hanford

Horizontal Damping Ratio (Page 382, Richart, Hall, + Woods)

$$B_x = \frac{(7-8\nu)\, m}{32(1-\nu)\rho r_0^3}, \quad D_x = \frac{0.288}{\sqrt{B_x}}$$

$$B_x = \frac{(7-8\times 0.37)(161)(259{,}968)(68)}{32(1-0.37)(105)(287.7)^3} = 0.2281$$

$$D_x = \frac{0.288}{\sqrt{0.2281}} = 0.603$$

Rocking Damping Ratio (Page 382, Richart, Hall, + Woods)

$$B_\psi = \frac{3(1-\nu)}{8}\,\frac{I_\psi}{\rho r_0^5}, \quad D_\psi = \frac{0.15}{(1+B_\psi)\sqrt{B_\psi}}$$

$$I_\psi = m\left(\frac{r_0^2}{4} + \frac{h^2}{3}\right),$$ Rocking about base.
Page 219, Richart, Hall, + Woods

$$I_\psi = \frac{\pi(287.7)^2(68)(161)}{(1728)(386.4)}\left\{\frac{(287.7)^2}{4} + \frac{(68)^2}{3}\right)$$

$$I_\psi = 94{,}799{,}090$$

$$B_\psi = \frac{\frac{3(1-0.37)}{8}\, I_\psi}{\left\{\frac{105}{(1728)(386.4)}\right\}(287.7)^5} = 0.072254$$

$$D_\psi = 0.520$$

PARSONS

Calculation Sheet

Job Number	Cost Center	Page Number	Sheet of

Rev	Date	By	Ck

Title END Station
Equivalent Damping
Hanford

Torsional Damping Ratio (Page 382, Richart, Hall, + Woods)

$$B_\theta = \frac{I_\theta}{\rho r_0^5} \quad , \quad D_\theta = \frac{0.50}{1 + 2B_\theta}$$

$$I_\theta = \frac{1}{2} m r_0^2$$

$$I_\theta = \frac{1}{2}\pi r_0^4 \frac{\gamma h}{g} = \frac{1}{2}\pi (287.7)^4 \left(\frac{161}{(386.4)}\right)\left(\frac{68}{1728}\right) =$$

$$B_\theta = \frac{\frac{1}{2}\pi (287.7)^4 \left(\frac{161}{386.4}\right)\left(\frac{68}{1728}\right)}{\left(\frac{(105)}{(1728)(386.4)}\right)(287.7)^5} = \frac{\pi (161)(68)}{2(105)(287.7)} = 0.56928$$

$$D_\theta = \frac{0.50}{1 + 2(0.56928)} = 0.234$$

PARSONS

Calculation Sheet

Job Number	Cost Center	Page Number	Sheet of

Rev	Date	By	Ck

Title End Station
Equivalent Damping
Hanford

Summary

Vertical	Mode	$\xi = 1.004$
Horizontal	Modes	$\xi = 0.603$
Rocking	Modes	$\xi = 0.520$
Torsional	Modes	$\xi = 0.234$

PARSONS

Calculation Sheet

Job Number	Cost Center	Page Number	Sheet of

Rev	Date	By	Ck

Title End Station
Area

Area

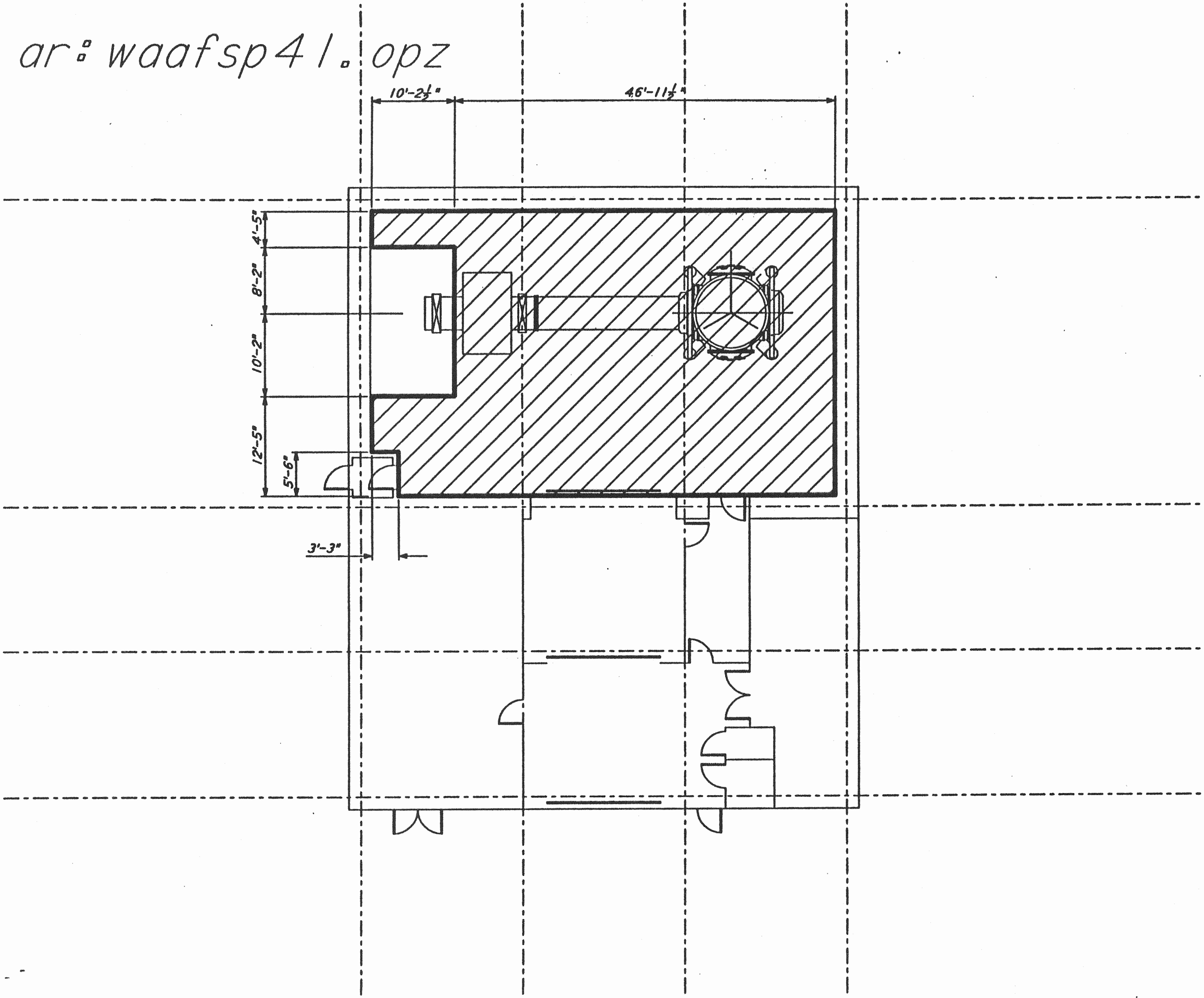
$(149 \times 122.5) - (39 \times 66) = 15,678.5$

$(422 - 369) \times (122.5) = 6,492.5$

$(686 - 122.5) \times (422) = 237,797.0$

Total $= 259,968 \text{ in}^2$

ar:waafsp41.opz



8/29/95

```
PRINT OF FREQUENCIES

MODE    CIRCULAR
NUMBER   FREQUENCY  FREQUENCY   PERIOD   TOLERANCE
        (RAD/SEC) (CYCLES/SEC)   (SEC)

   1    0.7106E+02 0.1131E+02 0.8843E-01 0.0000E+00

   2    0.7277E+02 0.1158E+02 0.8634E-01 0.5153E-15

   3    0.8317E+02 0.1324E+02 0.7554E-01 0.3944E-15

   4    0.8494E+02 0.1352E+02 0.7397E-01 0.2521E-15

   5    0.9710E+02 0.1545E+02 0.6471E-01 0.1157E-14

   6    0.1044E+03 0.1662E+02 0.6018E-01 0.3338E-15

   7    0.1610E+03 0.2562E+02 0.3903E-01 0.9827E-15

   8    0.1741E+03 0.2771E+02 0.3609E-01 0.1200E-15

   9    0.2733E+03 0.4350E+02 0.2299E-01 0.1948E-14

  10     0.3066E+03 0.4879E+02 0.2049E-01 0.1239E-14

  11     0.3190E+03 0.5078E+02 0.1969E-01 0.2860E-15

  12     0.3447E+03 0.5485E+02 0.1823E-01 0.6125E-15

  13     0.4054E+03 0.6453E+02 0.1550E-01 0.1239E-14

  14     0.4176E+03 0.6646E+02 0.1505E-01 0.1502E-14

  15     0.4689E+03 0.7462E+02 0.1340E-01 0.0000E+00

  16     0.5650E+03 0.8993E+02 0.1112E-01 0.7292E-15

  17     0.5917E+03 0.9417E+02 0.1062E-01 0.2976E-13

  18     0.5999E+03 0.9548E+02 0.1047E-01 0.1617E-15
```

```
19    0.6300E+03  0.1003E+03  0.9973E-02  0.7332E-15

20    0.6477E+03  0.1031E+03  0.9701E-02  0.1813E-10

21    0.7470E+03  0.1189E+03  0.8411E-02  0.1211E-07

22    0.8026E+03  0.1277E+03  0.7828E-02  0.1158E-09

23    0.8164E+03  0.1299E+03  0.7696E-02  0.1847E-05

24    0.8545E+03  0.1360E+03  0.7353E-02  0.3328E-05

25    0.8657E+03  0.1378E+03  0.7258E-02  0.1628E-07


PRINT OF EIGENVECTORS
```

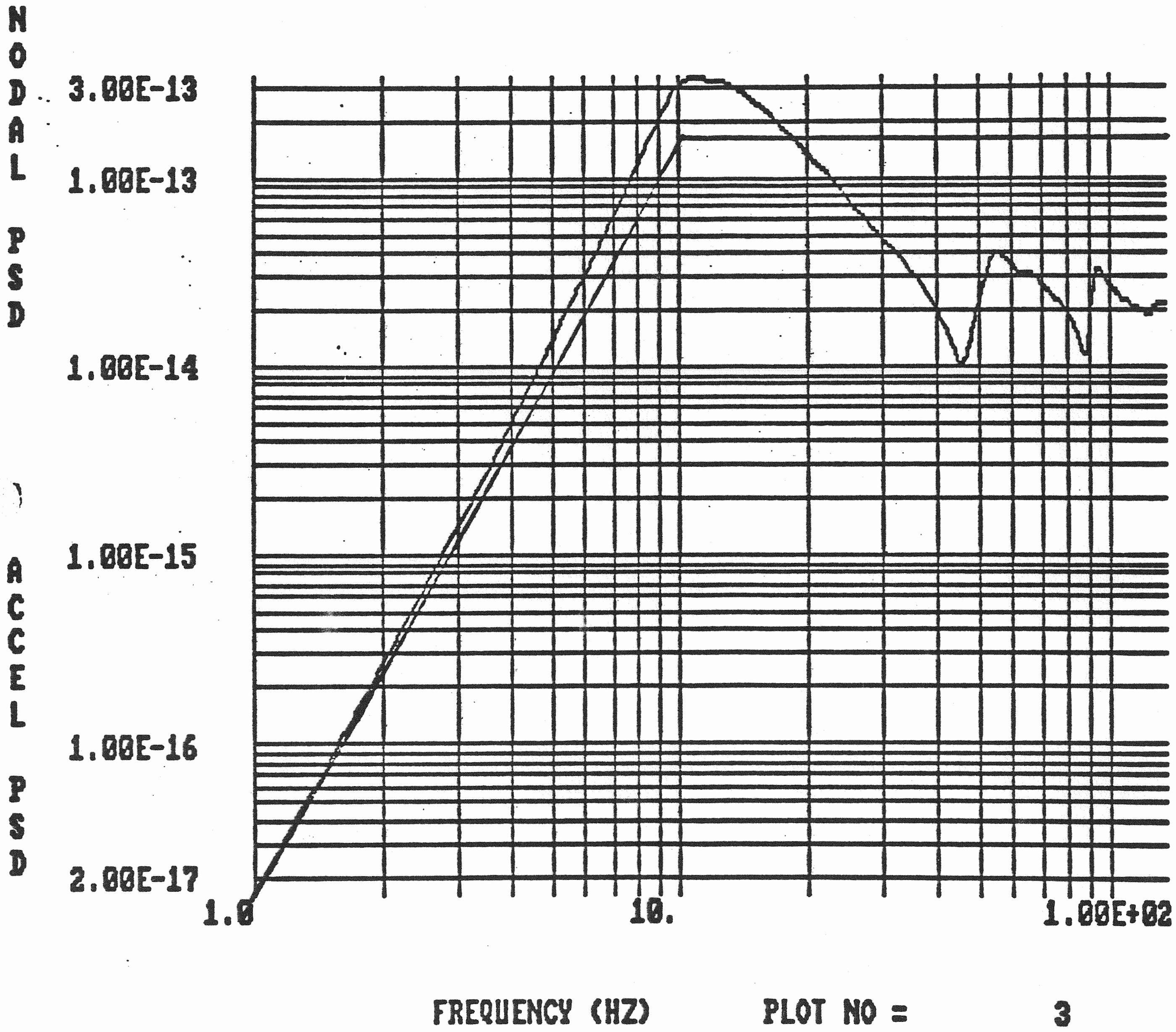
END-STATION FOUNDATION PSD ANALYSES

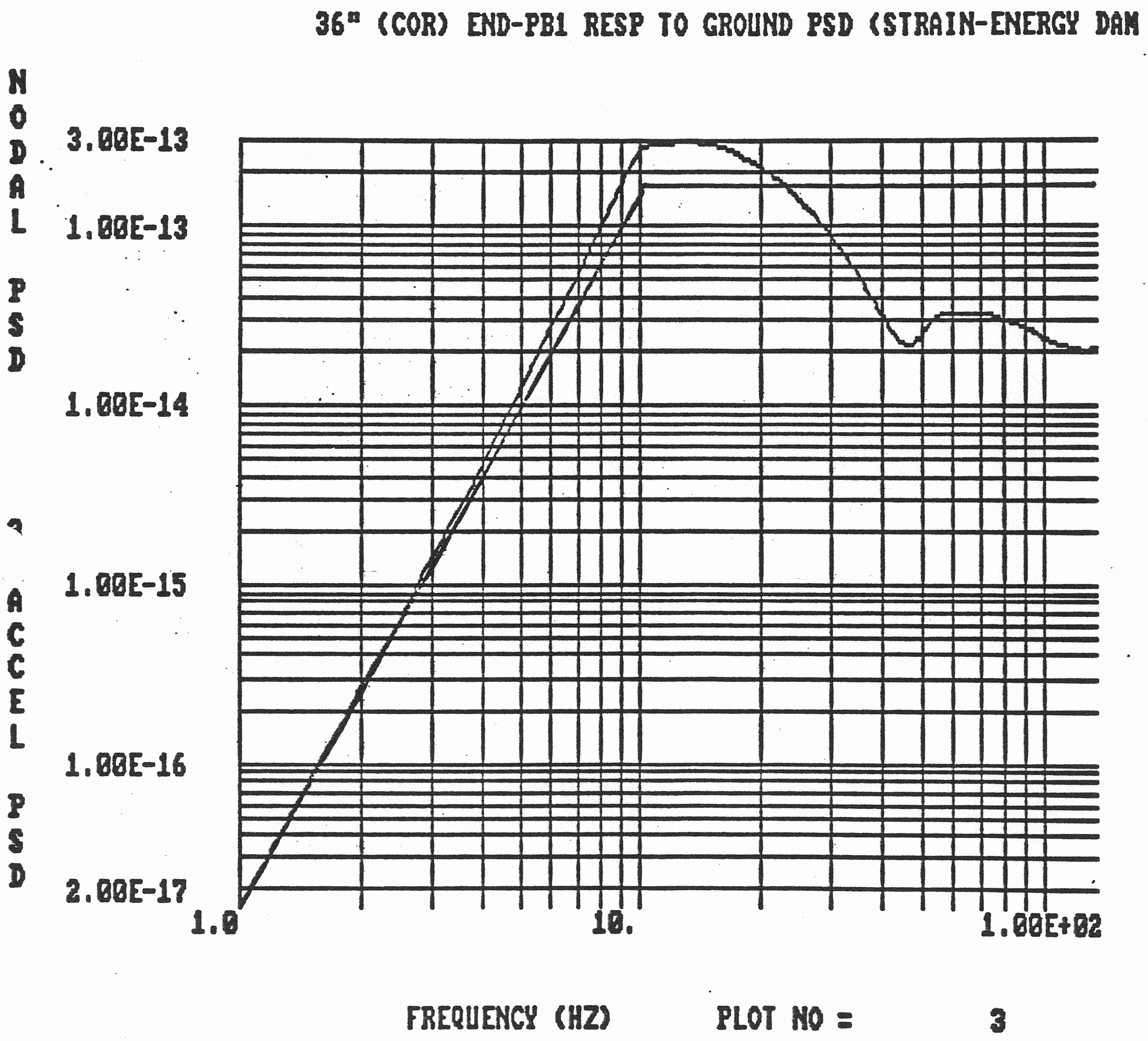
DAMPING FOR SOIL MATERIAL EQUAL TO 52.0% OF CRITICAL

DAMPING FOR CONCRETE MATERIAL EQUAL TO 2.0% OF CRITICAL

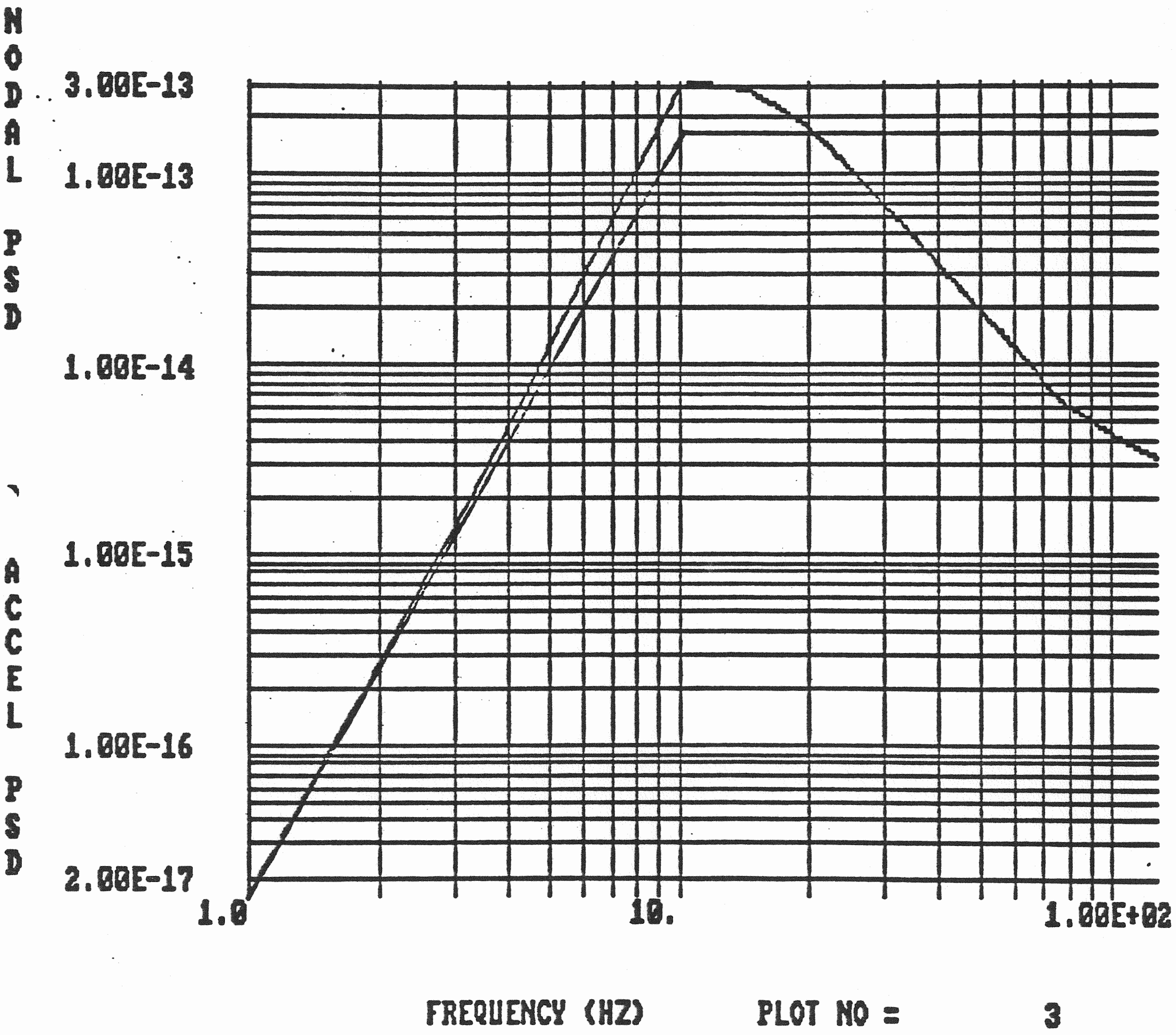
MODAL DAMPING CALCULATED IN PROPORTION TO STRAIN ENERGY

68 END-PB1 RESPONSE TO GROUND PSD (V DAMP 0.02) NODE 150




36" (COR) END-PB1 RESP TO GROUND PSD (STRAIN-ENERGY DAM
NODAL PSD / ACCEL PSD
3.00E-13
1.00E-13
1.00E-14
1.00E-15
1.00E-16
2.00E-17
1.0
10.
1.00E+02
FREQUENCY (HZ)
PLOT NO = 3

18" (COR) END-PB1 RESP TO GROUND PSD (STRAIN-ENERGY DAM



5. Acoustically Induced Vibrations

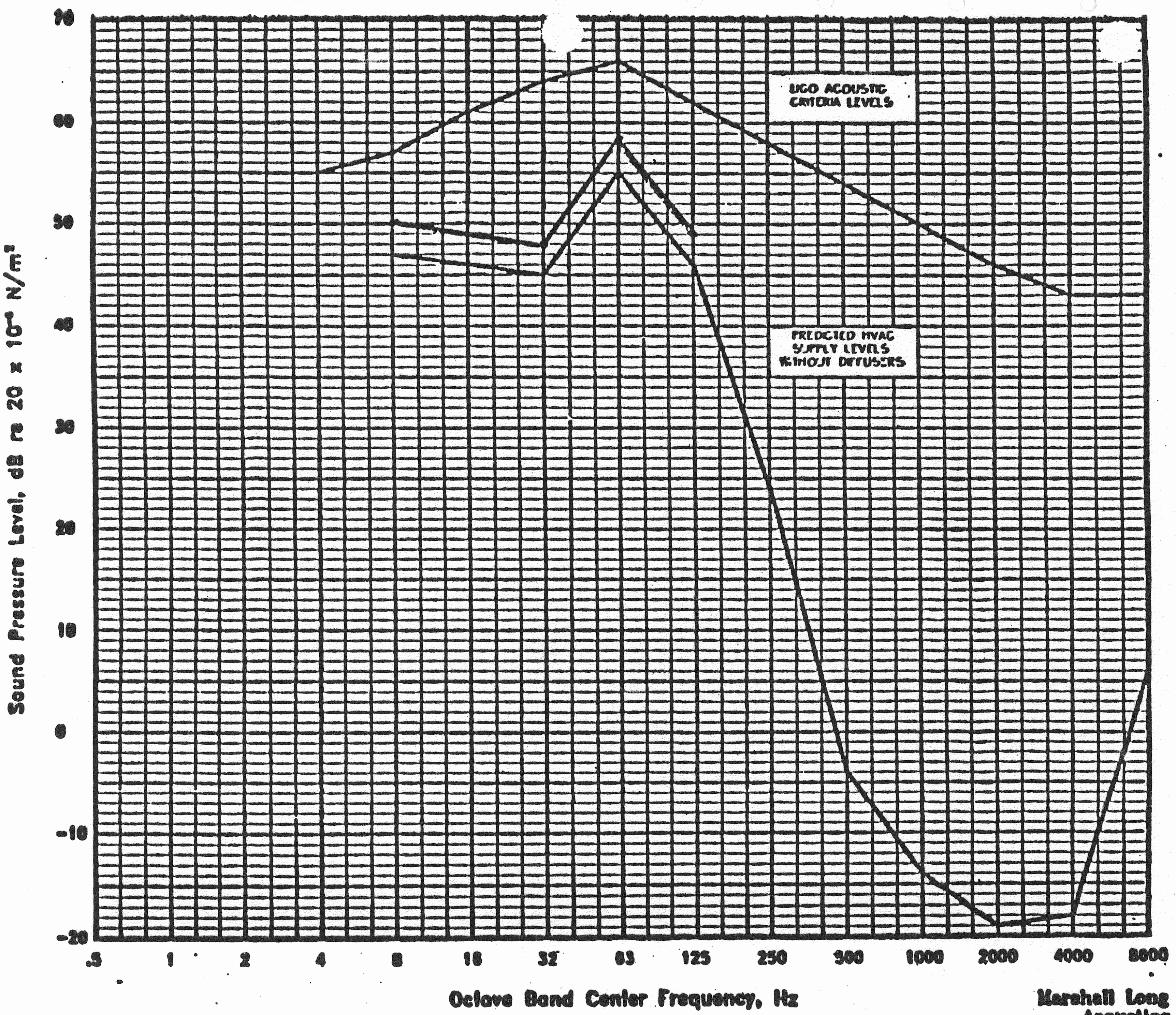
The acoustically induced vibration analyses used the LIGO acoustic criteria and an estimate made by Dr. Marshall Long of the expected acoustic pressure levels acting on the LVEA technical foundation. These acoustic pressure spectra were input directly into finite element models of the technical foundations using the STARDYNE computer code and the responses of the finite element models were calculated and shown as PSD spectra on top of the foundation slabs. The same finite element models that were used in the ambient vibration PSD analyses were used in determining the acoustic response of the technical foundation. The same soil properties were used as were discussed in the ambient PSD analyses including the soil damping values based on the strain energy method used to compute the equivalent modal damping. This method used the ratio of strain energy of the soil material to the strain energy of the concrete material in each mode to determine the modal damping values. As noted before this results in a decreasing modal damping from the large soil damping values of the fundamental modes to the lightly, 2%, damped modes of the concrete foundation.

The results of the acoustic analyses of the LVEA foundation indicated that the acoustically induced vibrations of an 18-inch thick foundation would exceed the vibration criteria which was a limit of one times the ambient PSD spectra. The 36-inch thick foundation would meet the vibration criteria with essentially no margin of safety. The 68-inch thick foundation would satisfy the PSD vibration criteria for acoustic inputs by a factor of about 5 to 7.

For the 68" thick technical foundations the acoustically induced vibrations are shown on the following two figures. The LVEA responses due to the LIGO Sound Pressure Level criteria are 1/7th of the LIGO Standard PSD. The LVEA responses for Marshall Long's expected sound pressure levels are 1/50th of the LIGO Standard PSD. Similarly for the Mid Stations (or End Stations) the responses are 1/5th and 1/50th of the LIGO Standard PSD for the LIGO Sound Pressure Level criteria and Marshall Long's expected sound pressure levels.

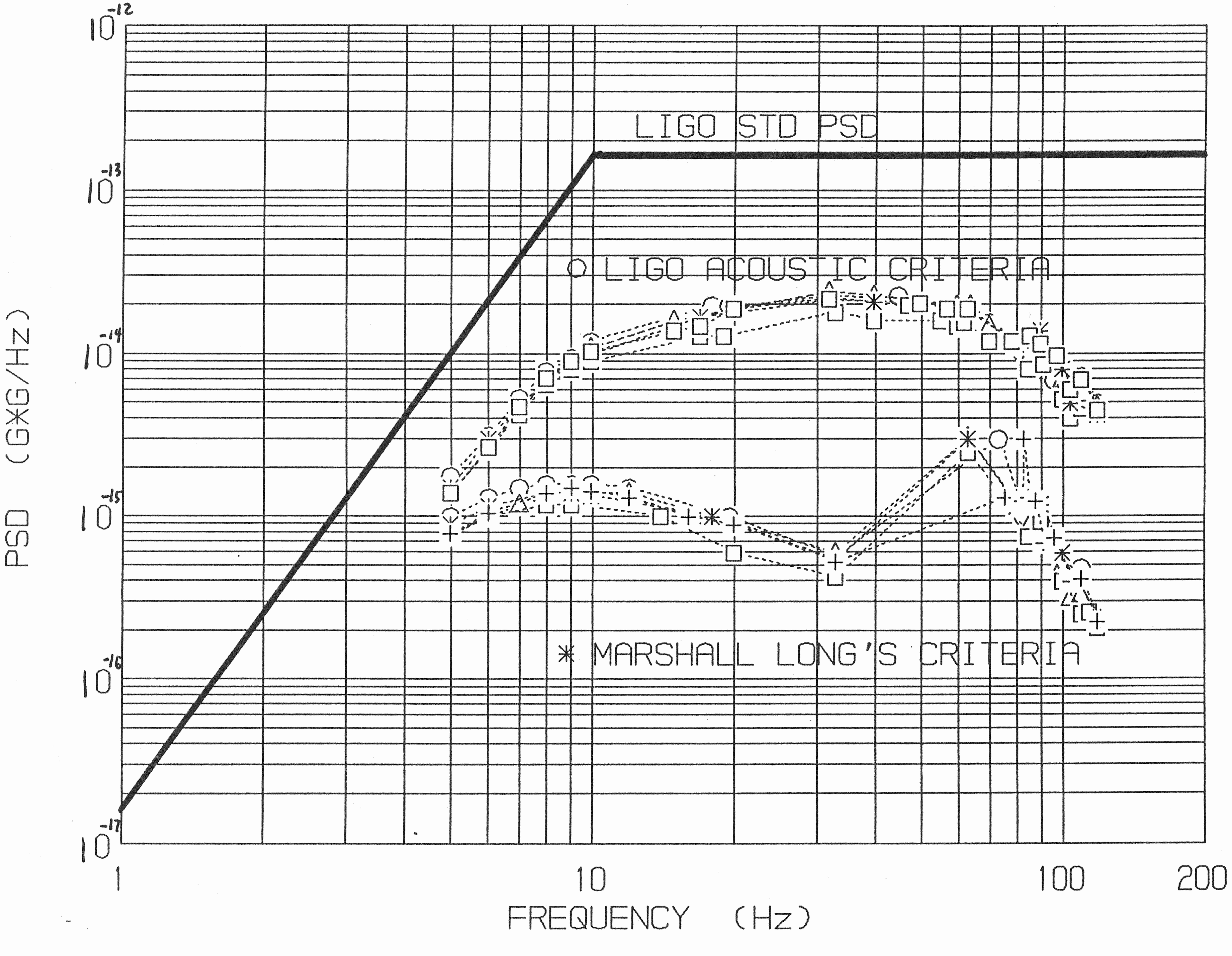
The last figure in this section shows the uncorrelated responses for the LIGO criteria PSD applied to the 68-inch thick LVEA foundation. The uncorreltaed spectrum, shown as a heavy solid line with solid dots, is lower than the correlated analysis result.

For reference, the STARDYNE (DYNRE3) user guide explanation of how the db values from sound pressure levels are input into the computer program are included at the end of this section

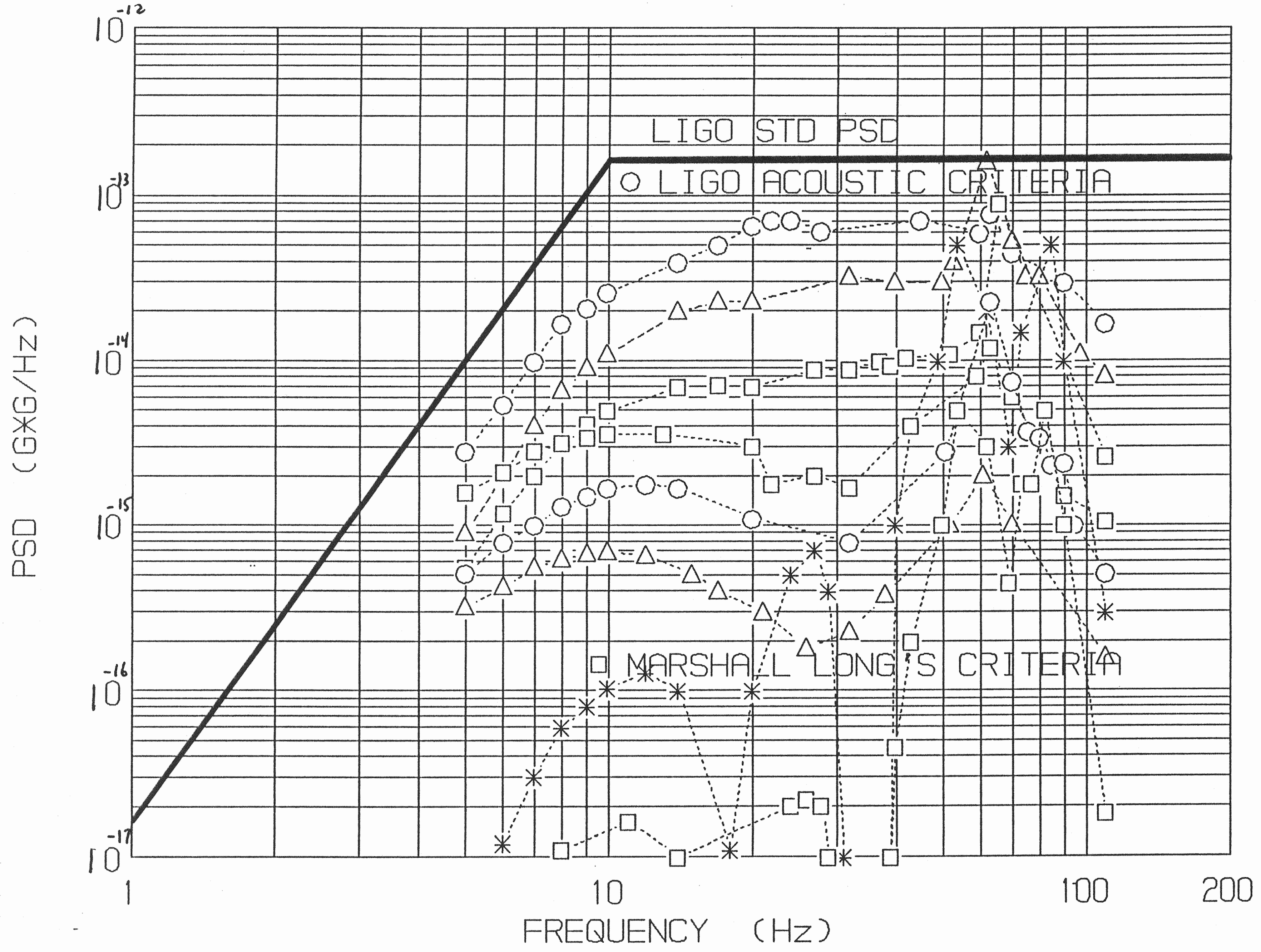


Marshall Long
Acoustics

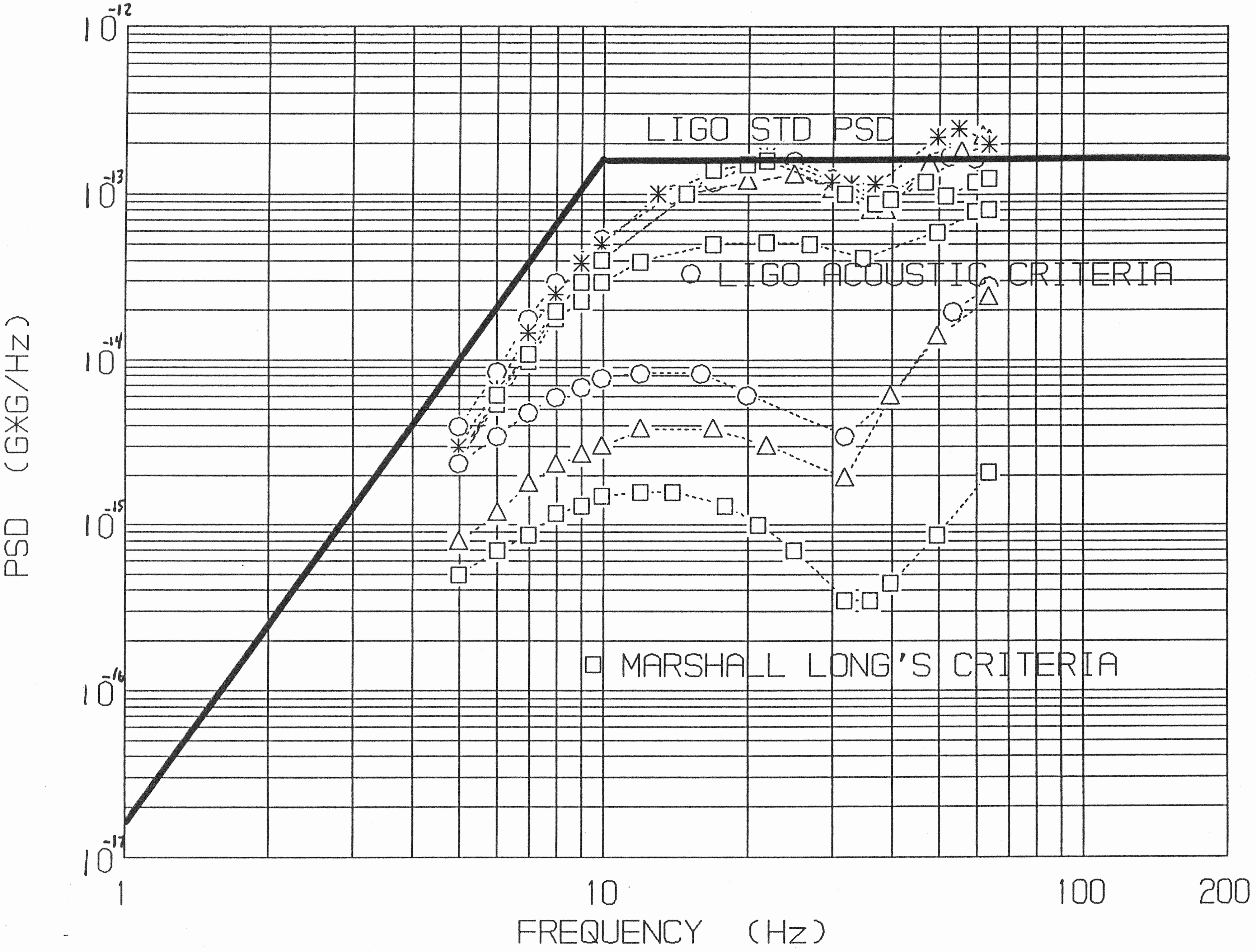
68" LVEA FOUNDATION - ACOUSTIC PSD



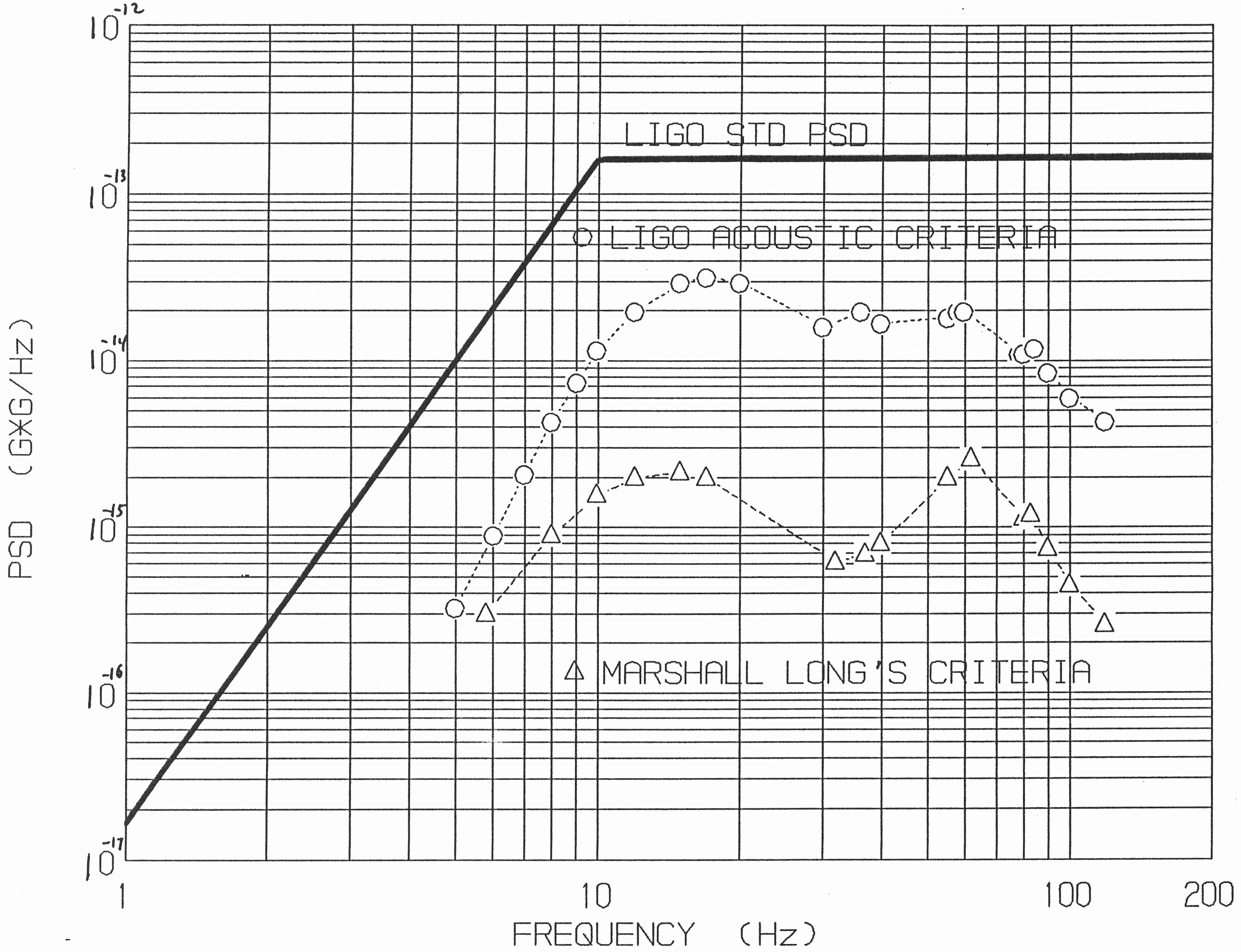
36" LVEA FOUNDATION - ACOUSTIC PSD



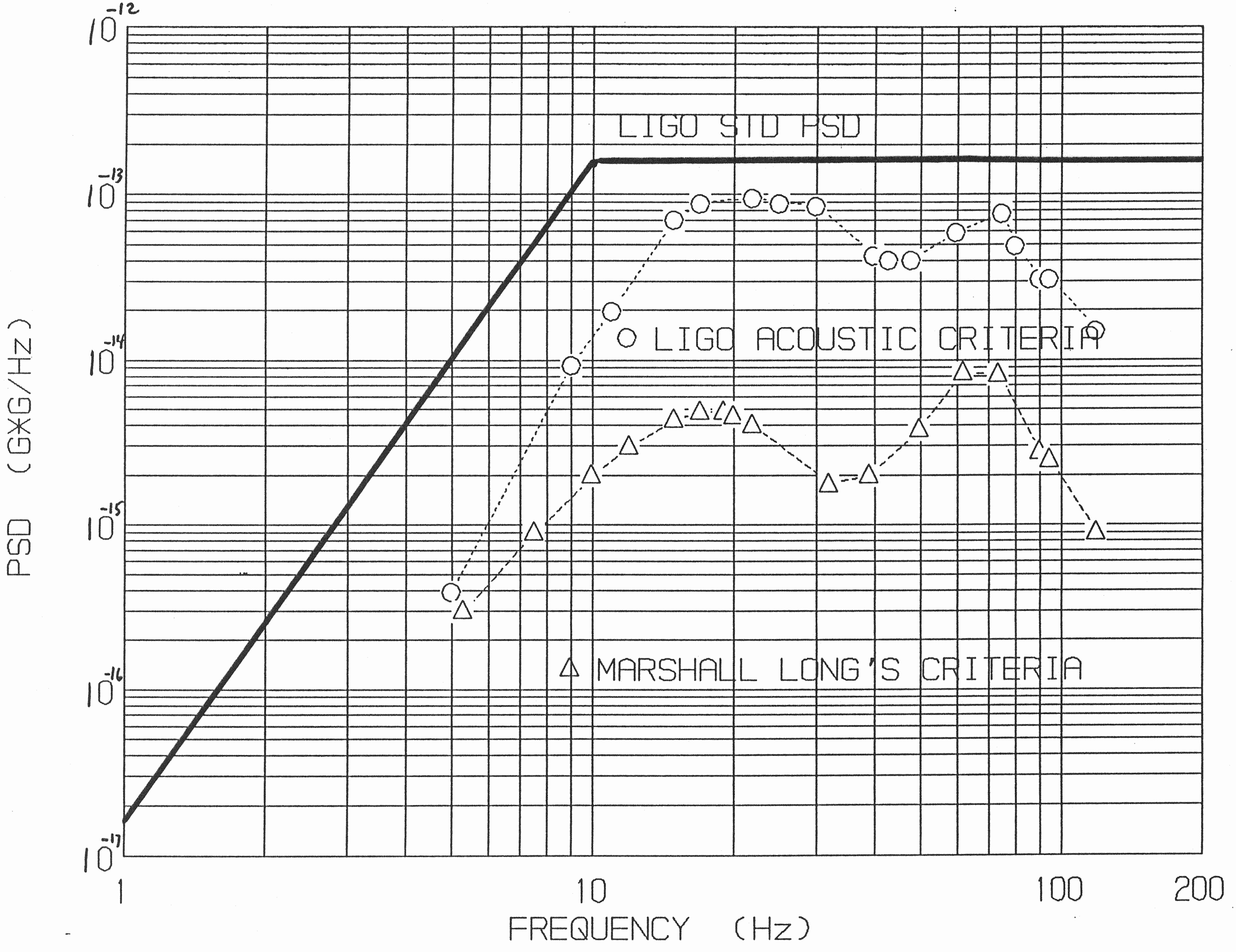
18" LVEA FOUNDATION - ACOUSTIC PSD



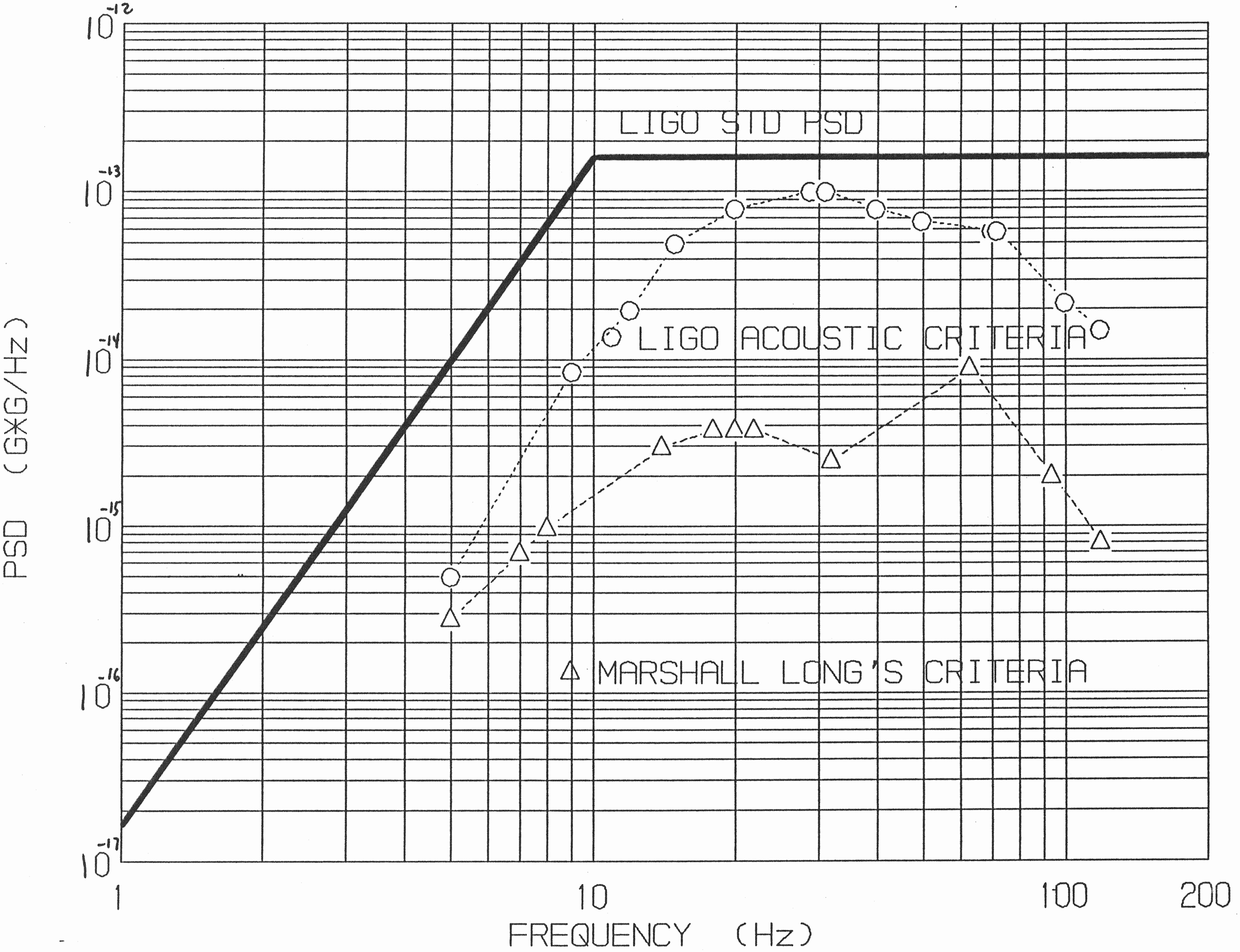
60" MID-STATION FOUNDATION - ACOUSTIC PSD



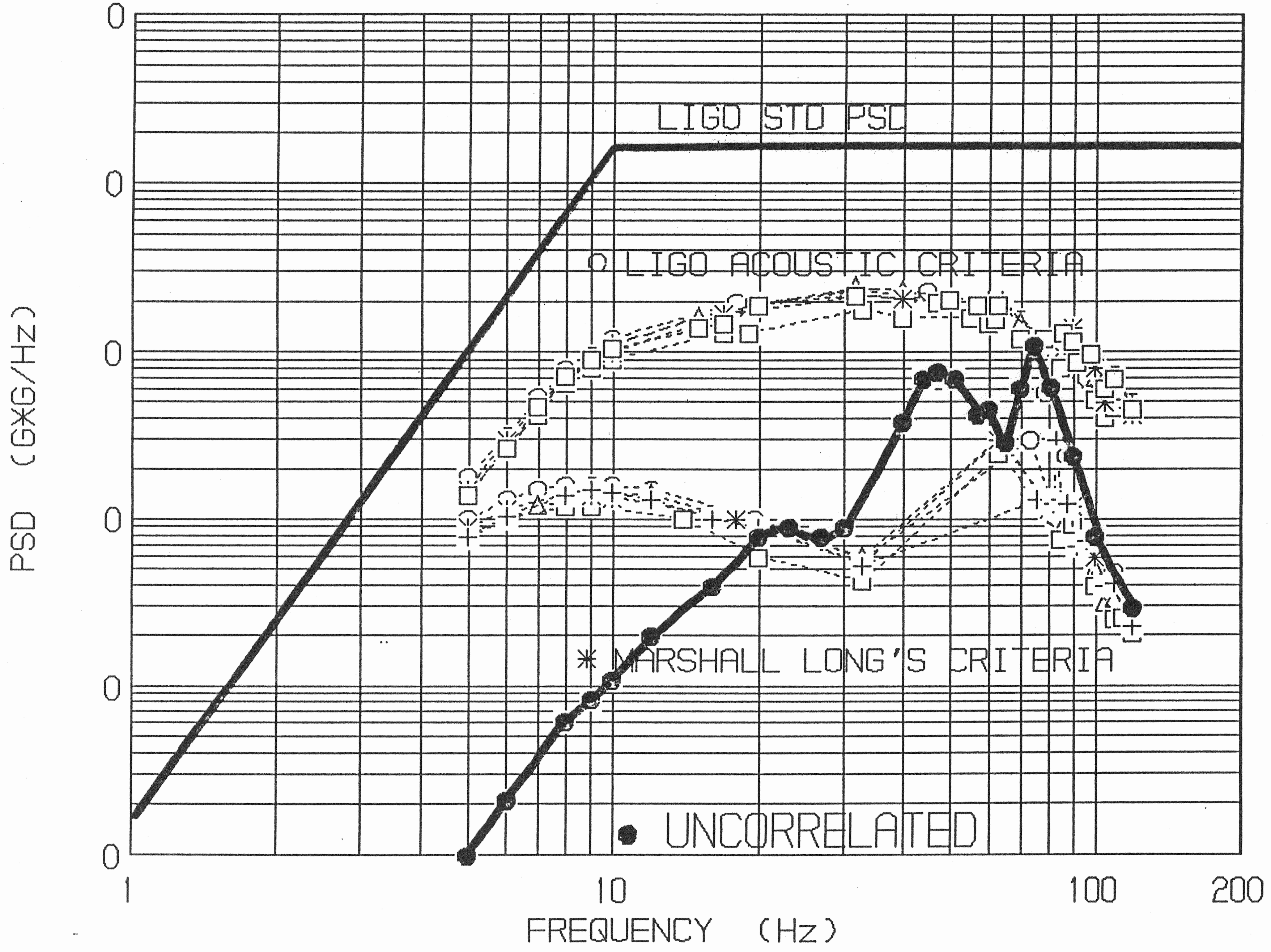
30" MID-STATION FOUNDATION - ACOUSTIC PSD



1[illegible]" MID-STATION FOUNDATION - ACOUSTIC PSD



68" LVEA FOUNDATION - ACOUSTIC PSD



INPUT FORMATS - CONTINUED

FORCING POWER SPECTRAL DATA - CONTINUED

(d) OCTAVE BAND POWER LEVEL FORCING TABLE - CONTINUED

(2) PSD FORMAT 2 (REQUIRED IF "PSD FORMAT" = 2, PAGE E-130) - This is one of two acoustic formats available to enter the Center Frequency of percent-octave-band and the Sound Pressure Level (SPL) for each band, in decibels. See table of Center Frequencies, page E-220. The entries may be on cards or tape as specified by IND, page E-136. The entries are DECRDN format as shown in Manual Section J.

1	2	12	22	32	42	52	62	72
▒	6	I	CF_i	P_i	CF_{i+1}	P_{i+1}	CF_{i+2}	P_{i+2}
		(I10)	(2F10.0)		(2F10.0)		(2F10.0)	

Enter 6 in column 2 of every data card.

I = DECRDN Card index. Start with 1 on first card and increment by 6 on each succeeding card. ***I must be negative on the last card.***

CF_i, P_i = Center frequency (HZ) and SPL, entered in pairs. Enter at least two pairs. After entry, the pairs will be sorted into ascending frequency order. If any 0.0 (or blank) ***Center Frequencies*** is encountered, that pair will be ignored. **IMPORTANT NOTE:** CF_1 must be less than or equal to FL and CF_N must be greater than or equal to FU (see page E-51). ***Within the FL → FU frequency range, ALL Center Frequencies shown on page E-220 must be entered.***

EXAMPLE: Given the following input data representing Acoustic Test Levels (Assume FL = 80.0 HZ and FU = 225.0 HZ)

1/3 Octave Band Center Frequency (HZ) (See page E-220)	Sound Pressure Level in 1/3 Octave Bands (db ref 2.9 x 10^{-9} lb/in^2
80	132.5
100	138.0
125	138.0
160	138.0
200	138.0
250	143.0

The input would be as follows:

Card No.	1	2	12	22	32	42	52	62	72
1	▒	6	1	80.0	132.5	100.0	138.0	125.0	138.0
2	▒	6	-7	160.0	138.0	200.0	138.0	250.0	143.0

NOTE: Each 1/3 Octave Band Center Frequency within the FL → FU range must be entered. In addition, PCT, on the Table Control card would be entered as 0.333 to correspond to 1/3 octave band levels. PO can be left blank, since a reference level of 2.9 $(10)^{-9}$ lb/in^2 would be assumed.

INPUT FORMATS - CONTINUED

FORCING POWER SPECTRAL DATA - CONTINUED

(d) OCTAVE BAND POWER LEVEL FORCING TABLE - CONTINUED

(3) PSD FORMAT 3 (REQUIRED IF "PSD FORMAT" = 3, PAGE E-130) - For this alternate acoustic input, DYNRE3 has pre-stored the lists of Center Frequency of percent-octave-bands shown on page E-220. This format is similar to PSD FORMAT = 2, and is used to enter the Sound Pressure Level (SPL) for each band in decibels (associated with the pre-stored Center Frequencies). The entries may be on cards or tape as specified by IND page E-136. The entries are DECRDN format as shown in Manual Section J.

1	2	12	22	32	42	52	62	72	
▦	6	I	CF_i	P_i	P_{i+1}	P_{i+2}	ETC.	ETC.	
(IX)	(I1)	(I10)	(F10.0)	(F10.0)	(F10.0)	(F10.0)	(F10.0)	(F10.0)	

Enter 6 in column 2 of every data card.

I = DECRDN Card index. Start with 1 on first card and increment by 6 on each succeeding card. ***I must be negative on the last card.***

CF_i = The first (lowest) of the Center Frequencies used for the power level inputs. See example, below. This number must exactly match one of the Center Frequencies shown on page E-220.
IMPORTANT NOTE: CF_i must be ***less*** than or equal to FL and the Center Frequency associated with P_N must be ***greater*** than or equal to FU (see page E-51.

P_i = The SPL's associated with the series of pre-stored Center Frequencies beginning with CF_i. P_i is associated with CF_i; P_{i+1} is associated with CF_{i+1}; etc. The power levels must be entered in ascending, consecutive Center Frequency order. Do not skip the power level for any intermediate Center Frequency. At least two power levels must be entered.

EXAMPLE: Using the Acoustic Test Level input example of page E-163, the entries for PSD FORMAT = 3 would be made as follows:

Card No.	1	2	12	22	32	42	52	62	72	
1	▦	6	1	80.0	132.5	138.0	138.0	138.0	138.0	
2	▦	6	-7	143.0						

This would enter power levels for the series of Center Frequencies 80.0 HZ through 250.0 HZ, as shown on page E-220.

INPUT FORMATS - CONTINUED

FORCING POWER SPECTRAL DATA - CONTINUED

(d) OCTAVE BAND POWER LEVEL FORCING TABLE - CONTINUED

(2) PSD FORMAT 2 (REQUIRED IF "PSD FORMAT" = 2, PAGE E-130) - This is one of two acoustic formats available to enter the Center Frequency of percent-octave-band and the Sound Pressure Level (SPL) for each band, in decibels. See table of Center Frequencies, page E-220. The entries may be on cards or tape as specified by IND, page E-136. The entries are DECRDN format as shown in Manual Section J.

1	2	12	22	32	42	52	62	72	
▒	6	I	CF_i	P_i	CF_{i+1}	P_{i+1}	CF_{i+2}	P_{i+2}	
		(I10)	(2F10.0)		(2F10.0)		(2F10.0)		

Enter 6 in column 2 of every data card.

I = DECRDN Card index. Start with 1 on first card and increment by 6 on each succeeding card. *I must be negative on the last card.*

CF_i, P_i = Center frequency (HZ) and SPL, entered in pairs. Enter at least two pairs. After entry, the pairs will be sorted into ascending frequency order. If any 0.0 (or blank) *Center Frequencies* is encountered, that pair will be ignored. **IMPORTANT NOTE:** CF_1 must be less than or equal to FL and CF_N must be greater than or equal to FU (see page E-51). *Within the FL → FU frequency range, **ALL** Center Frequencies shown on page E-220 must be entered.*

EXAMPLE: Given the following input data representing Acoustic Test Levels (Assume FL = 80.0 HZ and FU = 225.0 HZ)

1/3 Octave Band Center Frequency (HZ) (See page E-220)	Sound Pressure Level in 1/3 Octave Bands (db ref 2.9×10^{-9} lb/in^2
80	132.5
100	138.0
125	138.0
160	138.0
200	138.0
250	143.0

The input would be as follows:

Card No.	1	2	12	22	32	42	52	62	72	
1	▒	6	1	80.0	132.5	100.0	138.0	125.0	138.0	
2	▒	6	-7	160.0	138.0	200.0	138.0	250.0	143.0	

NOTE: Each 1/3 Octave Band Center Frequency within the FL → FU range must be entered. In addition, PCT, on the Table Control card would be entered as 0.333 to correspond to 1/3 octave band levels. PO can be left blank, since a reference level of $2.9 (10)^{-9}$ lb/in^2 would be assumed.

FORCING POWER SPECTRAL DATA - CONTINUED

(d) OCTAVE BAND POWER LEVEL FORCING TABLE - CONTINUED

(3) PSD FORMAT 3 (REQUIRED IF "PSD FORMAT" = 3, PAGE E-130) - For this alternate acoustic input, DYNRE3 has pre-stored the lists of Center Frequency of percent-octave-bands shown on page E-220. This format is similar to <u>PSD FORMAT = 2</u>, and is used to enter the Sound Pressure Level (SPL) for each band in decibels (associated with the pre-stored Center Frequencies). The entries may be on cards or tape as specified by <u>IND</u> page E-136. The entries are DECRDN format as shown in Manual Section J.

1	2	12	22	32	42	52	62	72	
▨	6	I	CF_i	P_i	P_{i+1}	P_{i+2}	ETC.	ETC.	
(IX)	(I1)	(I10)	(F10.0)	(F10.0)	(F10.0)	(F10.0)	(F10.0)	(F10.0)	

Enter <u>6</u> in column 2 of every data card.

I = DECRDN Card index. Start with 1 on first card and increment by 6 on each succeeding card. *I must be negative on the last card.*

CF_i = The first (lowest) of the Center Frequencies used for the power level inputs. See example, below. This number must exactly match one of the Center Frequencies shown on page E-220.
IMPORTANT NOTE: CF_i must be *less* than or equal to FL and the Center Frequency associated with P_N must be *greater* than or equal to FU (see page E-51.

P_i = The SPL's associated with the series of pre-stored Center Frequencies beginning with CF_i. P_i is associated with CF_i; P_{i+1} is associated with CF_{i+1}; etc. The power levels must be entered in ascending, consecutive Center Frequency order. Do not skip the power level for any intermediate Center Frequency. At least two power levels must be entered.

EXAMPLE: Using the Acoustic Test Level input example of page E-163, the entries for PSD FORMAT = 3 would be made as follows:

Card No.	1	2	12	22	32	42	52	62	72	
1	▨	6	1	80.0	132.5	138.0	138.0	138.0	138.0	
2	▨	6	-7	143.0						

This would enter power levels for the series of Center Frequencies 80.0 HZ through 250.0 HZ, as shown on page E-220.

DYNRE3 USER'S GUIDE

APPENDIX - CONTINUED

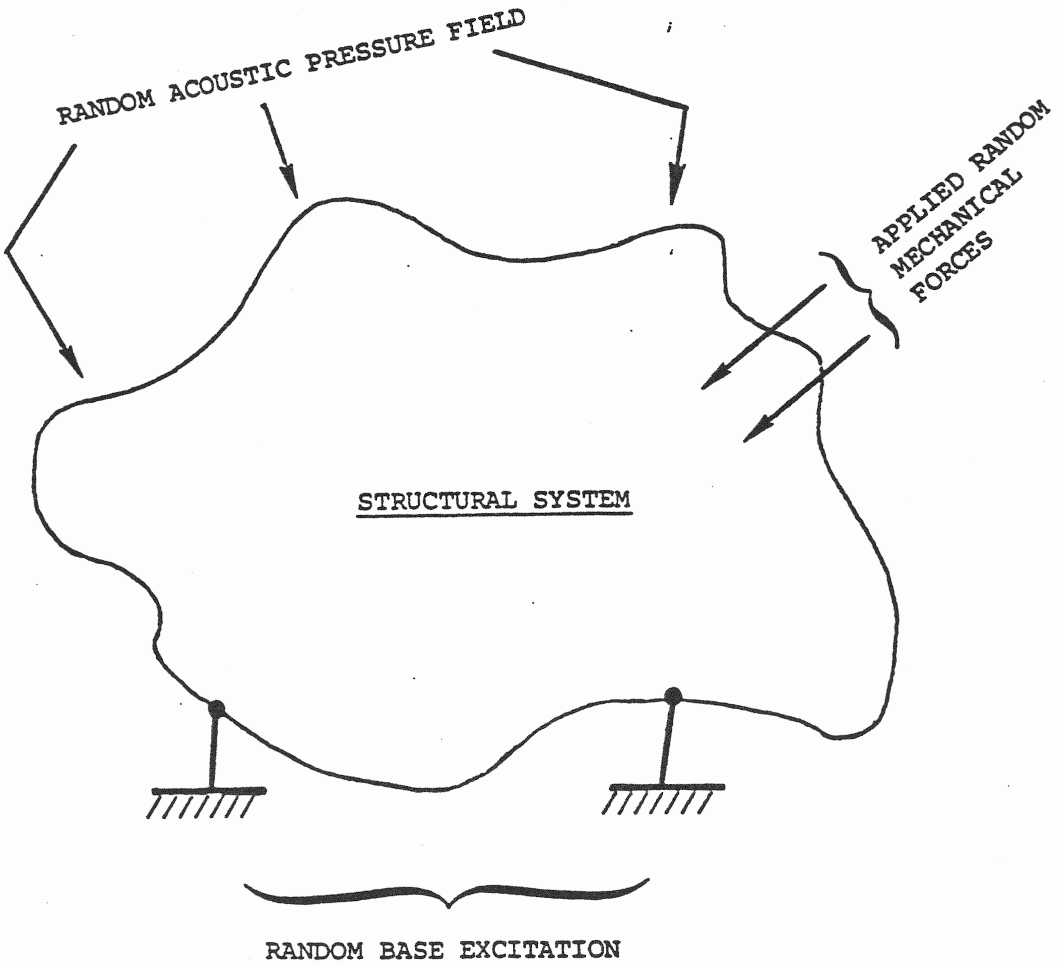
OCTAVE BAND TABLES - Use for PSD FORMATS 2 and 3, pages E-163 and E-165.

STANDARD OCTAVE BANDS	
(PCT = 1.0)	
NUMBER	BAND CENTER FREQUENCY (HZ)
1	1.0
2	2.0
3	4.0
4	8.0
5	16.0
6	31.5
7	63
8	125
9	250
10	500
11	1000
12	2000
13	4000
14	8000
15	16,000

STANDARD ONE THIRD OCTAVE BANDS			
(PCT = .333)			
NUMBER	BAND CENTER FREQUENCY (HZ)	NUMBER	BAND CENTER FREQUENCY (HZ)
1	1.0	23	160
2	1.25	24	200
3	1.60	25	250
4	2.0	26	315
5	2.5	27	400
6	3.18	28	500
7	4.0	29	630
8	5.0	30	800
9	6.35	31	1000
10	8.0	32	1250
11	10.0	33	1600
12	12.7	34	2000
13	16.0	35	2500
14	20.0	36	3150
15	25.0	37	4000
16	31.5	38	5000
17	40	39	6300
18	50	40	8000
19	63	41	10,000
20	80	42	12,500
21	100	43	16,000
22	125		

- If there are only minor variations in power levels, use the STANDARD OCTAVE BAND. If there are major variations in power level, the greater flexibility of the STANDARD ONE THIRD OCTAVE BAND might be preferable.

TYPICAL DYNRE3 APPLICATIONS AND SUMMARY



The above figure depicts a typical DYNRE3 analysis.

(The structural system is being excited by one or more stationary random loadings).

6. Thermally Induced Deformations

Thermally induced deformations were based on air temperature changes at a rate of 2 °F per hour. Since the time duration of interest is about ten minutes, this relates to a temperature change of 0.33 °F in ten minutes. The film coefficient for the transfer of heat from air to a solid surface varies from 1 to 4 for convection processes. For these analyses a value of 2 was selected to minimize the transfer of heat from the air into the concrete technical foundation and is consistent with the low air velocities expected in the LVEA. The thermal conductivity for concrete is 0.54 BTU/HR-FT-F. The specific heat is 0.2 BTU/LB-F. The density of the concrete is 144 LB/FT^3.

The thermal analysis of the transient heat transfer from the air to the concrete concluded that after ten minutes the air temperature would increase by 0.33 °F, the concrete surface temperature would increase to 0.28 °F, at one inch below the surface the concrete temperature would increase by 0.10 °F, at two inches below the concrete surface the temperature would increase by 0.02 °F, and at three inches below the concrete surface no significant change in the concrete temperature would occur. These temperature changes with respect to the concrete depth were input into a two dimensional finite element model of the technical foundation as it is supported on the soil.

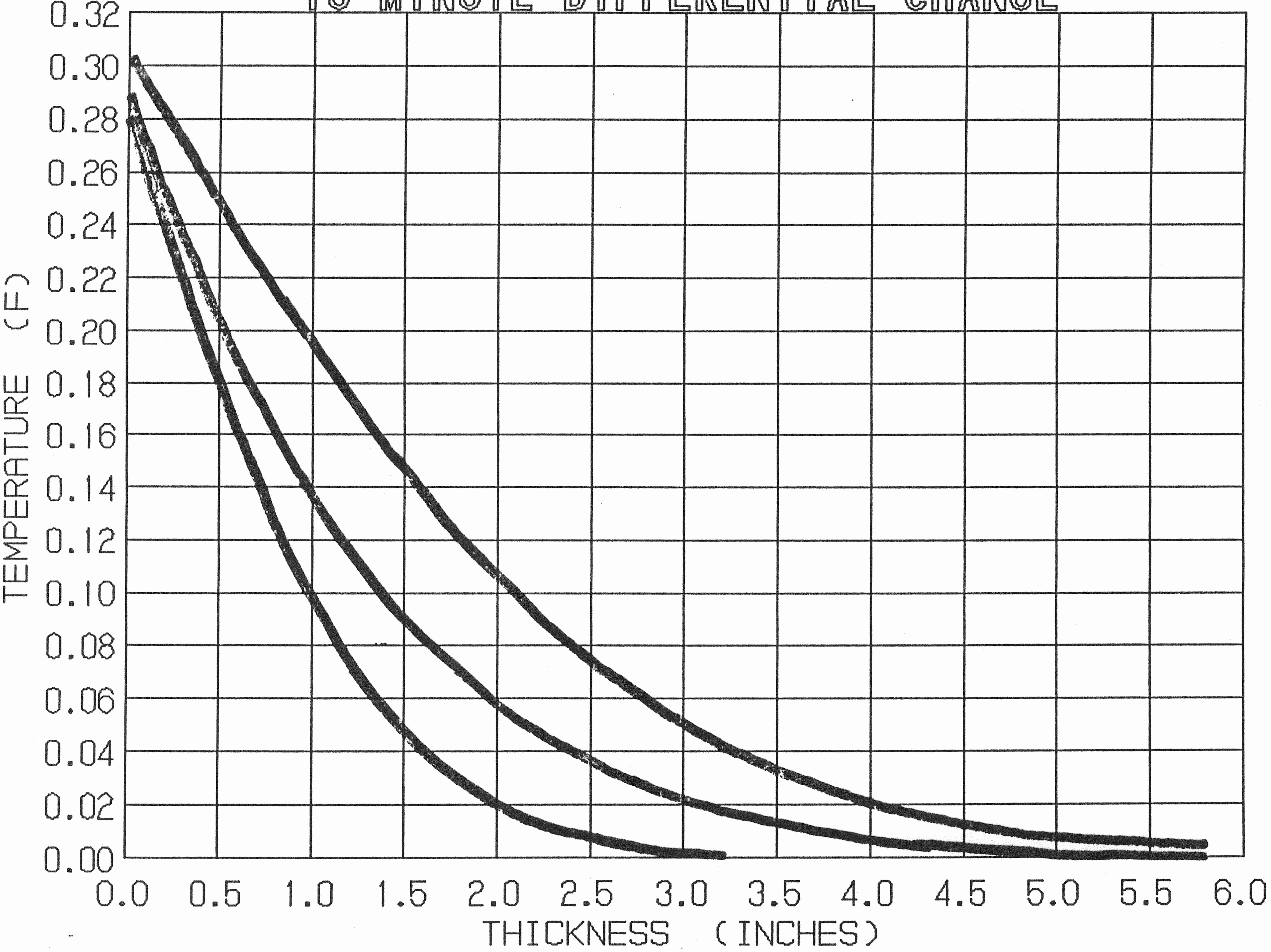
The finite element models were varied to include various foundation thicknesses and foundation lengths. The resulting finite element deformation calculations indicated that the edges of the foundations would exceed the fifty nano-radian relative rotation over a two meter foundation length. This region of high rotations is defined by a zone that extends inward approximately 30 feet from the edge of the foundation slab.

Note that a building heat load analysis conducted after the PDR indicated that the rate of air temperature change used in this analysis might be high by a factor two. Thus instead of an air temperature change of 0.33 °F in ten minutes, the air temperature may only change 0.16 °F in ten minutes during the solar heating of the building during late morning or cooling of the exterior building surface temperatures in the late afternoon. Based on these modifications to the rate of heating or cooling of the interior air temperatures it could be expected that only the perimeter of the LVEA foundation defined by a 15 foot wide zone around the perimeter of the foundation would exceed the fifty nano-radian relative rotation criteria over a two meter long foundation length. Also it should be noted that at other times when the air temperatures are more stable over the technical foundation it is not expected that the foundation will be distorting as rapidly as predicted in these analyses and therefore most of the foundation surface should not experience fifty nano-radian rotations over a ten minute duration. Note the reason for selecting a ten minute duration is related to the time required to obtain lock after an upset has occurred. During this ten minute time the relative rotations must be less than fifty nano-radians over a two meter foundation length in order to regain lock.

A heat load analysis was also conducted for extreme temperature variations caused by cloud cover or the rapid changes associated with weather fronts. The conclusions of this study indicate that a one degree temperature change of the air can occur in about 36 minutes. Thus it is evident that the air temperature changes of the magnitude assumed in this study can occur but may be limited to specific weather conditions and not necessarily recurring every day.

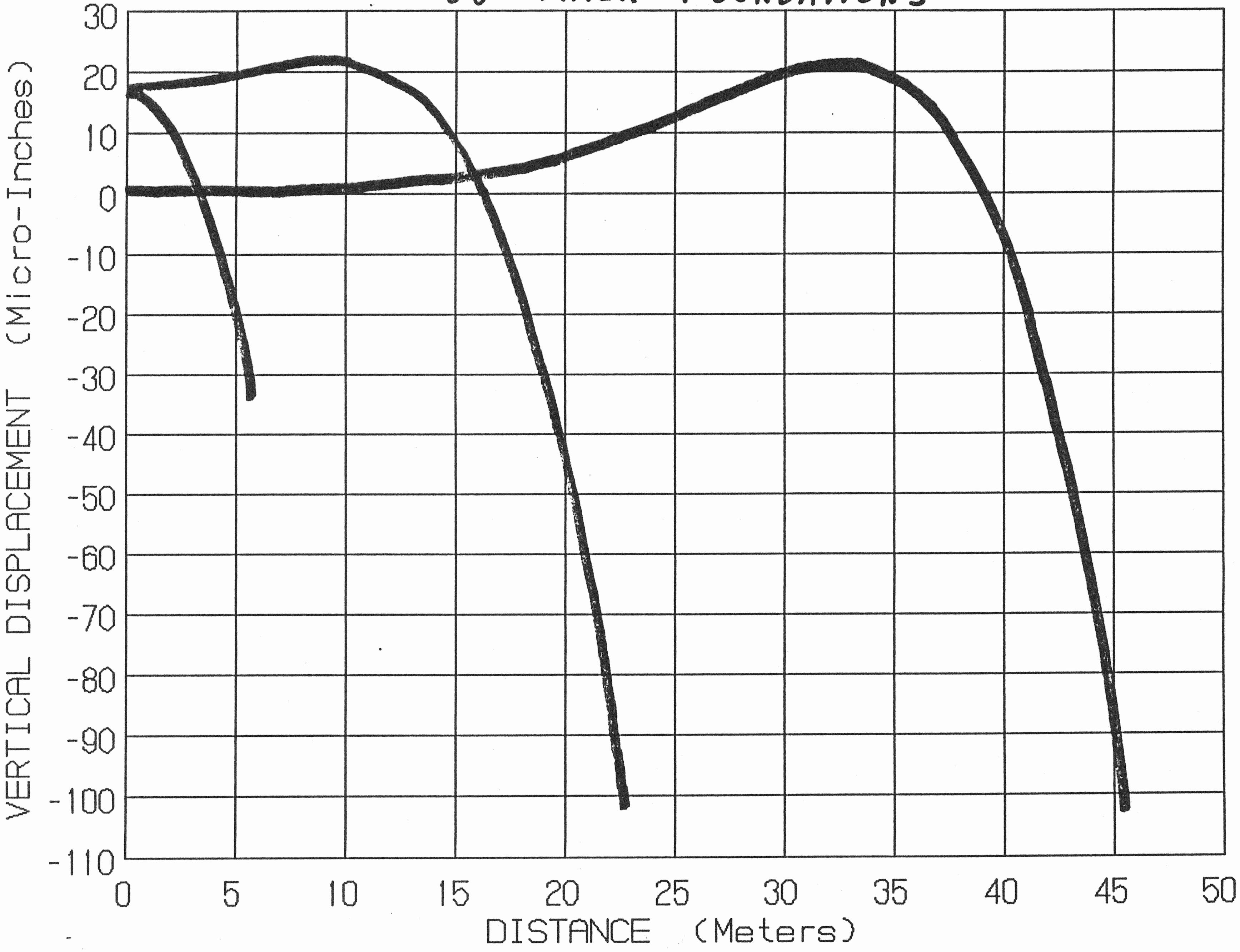
2 F TEMPERATURE CHANGE PER HOUR

10 MINUTE DIFFERENTIAL CHANGE



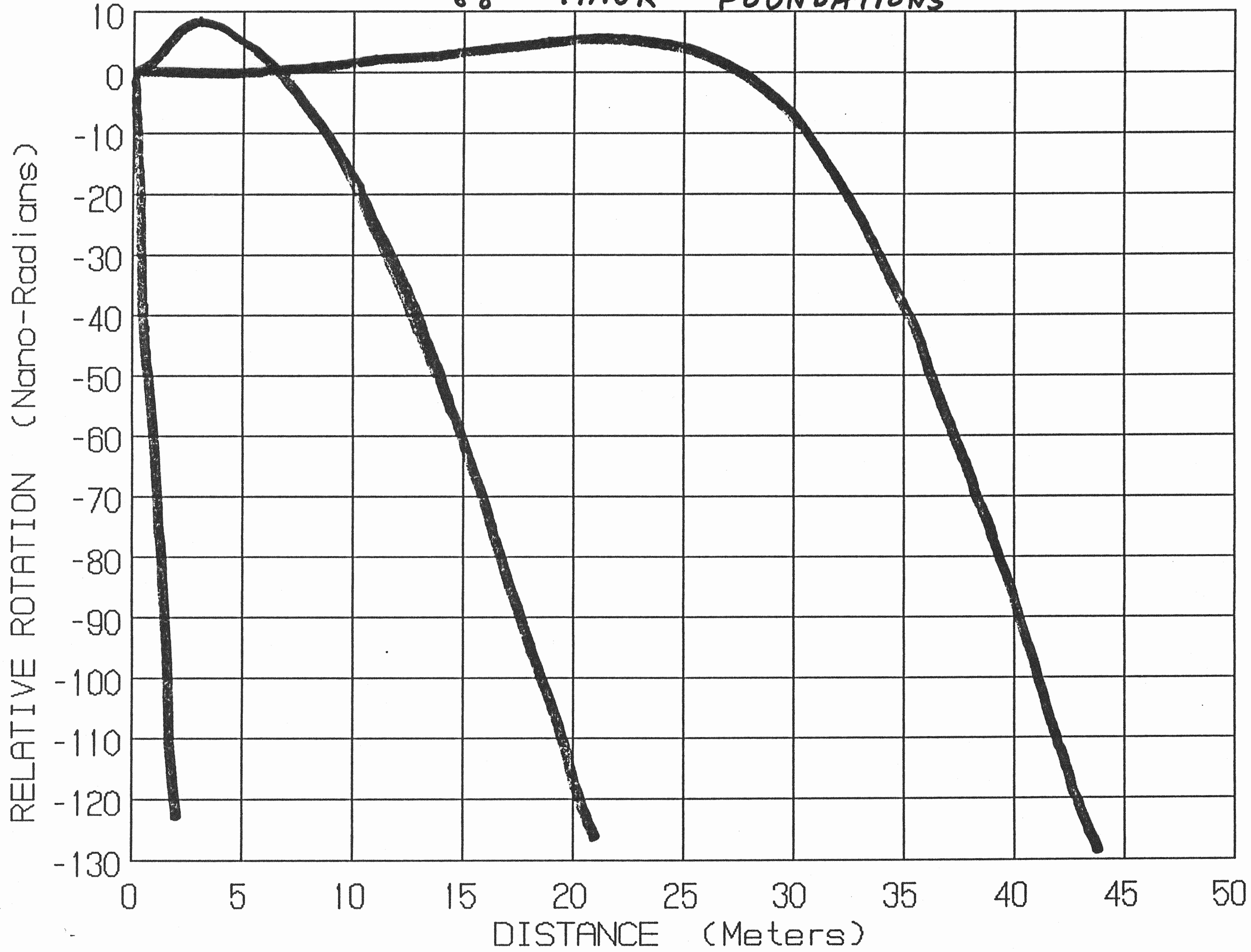
10 MINUTE THERMAL FOUNDATION DEFORMATIONS

68" THICK FOUNDATIONS

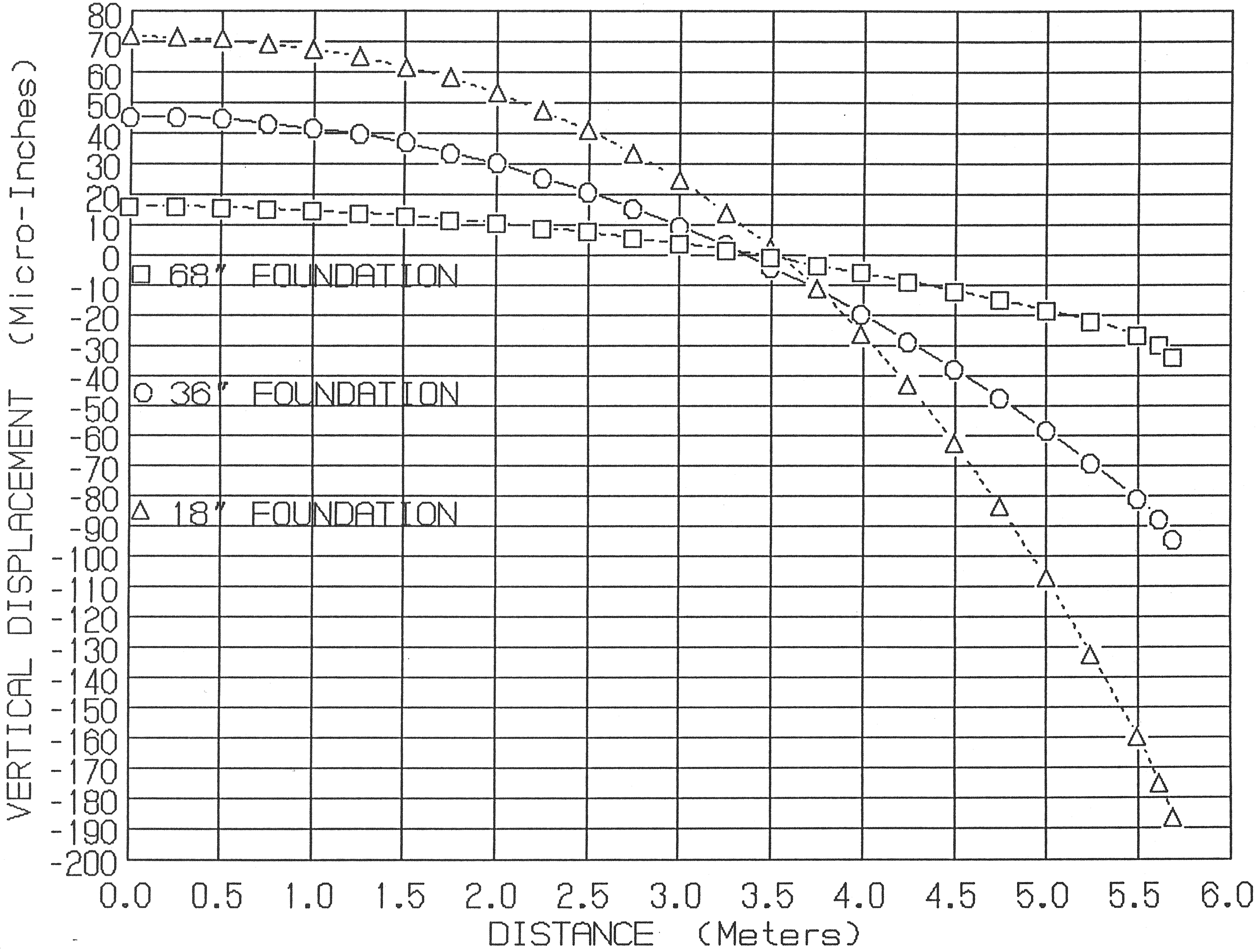


10 MINUTE THERMAL FOUNDATION ROTATIONS

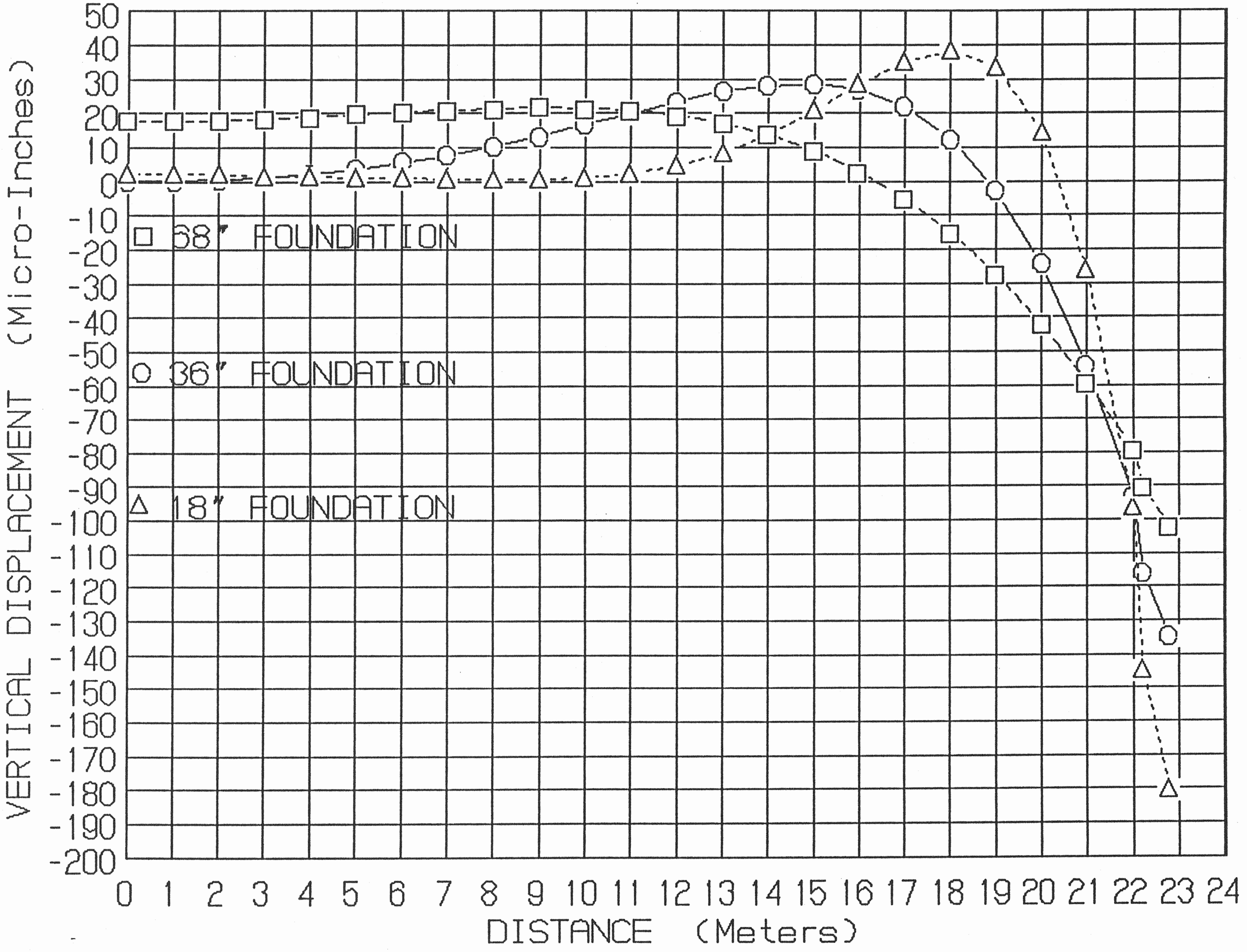
68" THICK FOUNDATIONS



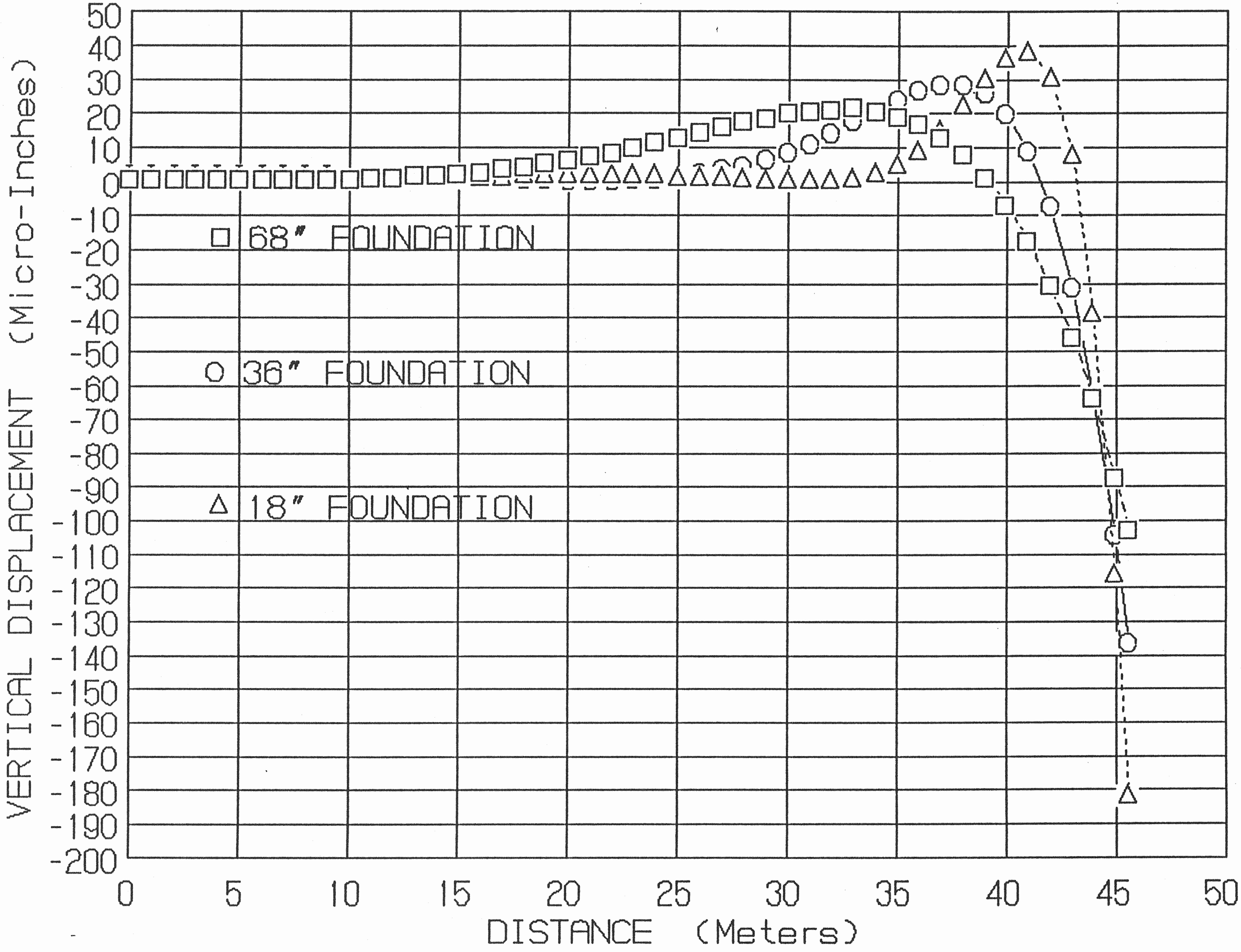
10 MINUTE THERMAL FOUNDATION DEFORMATIONS



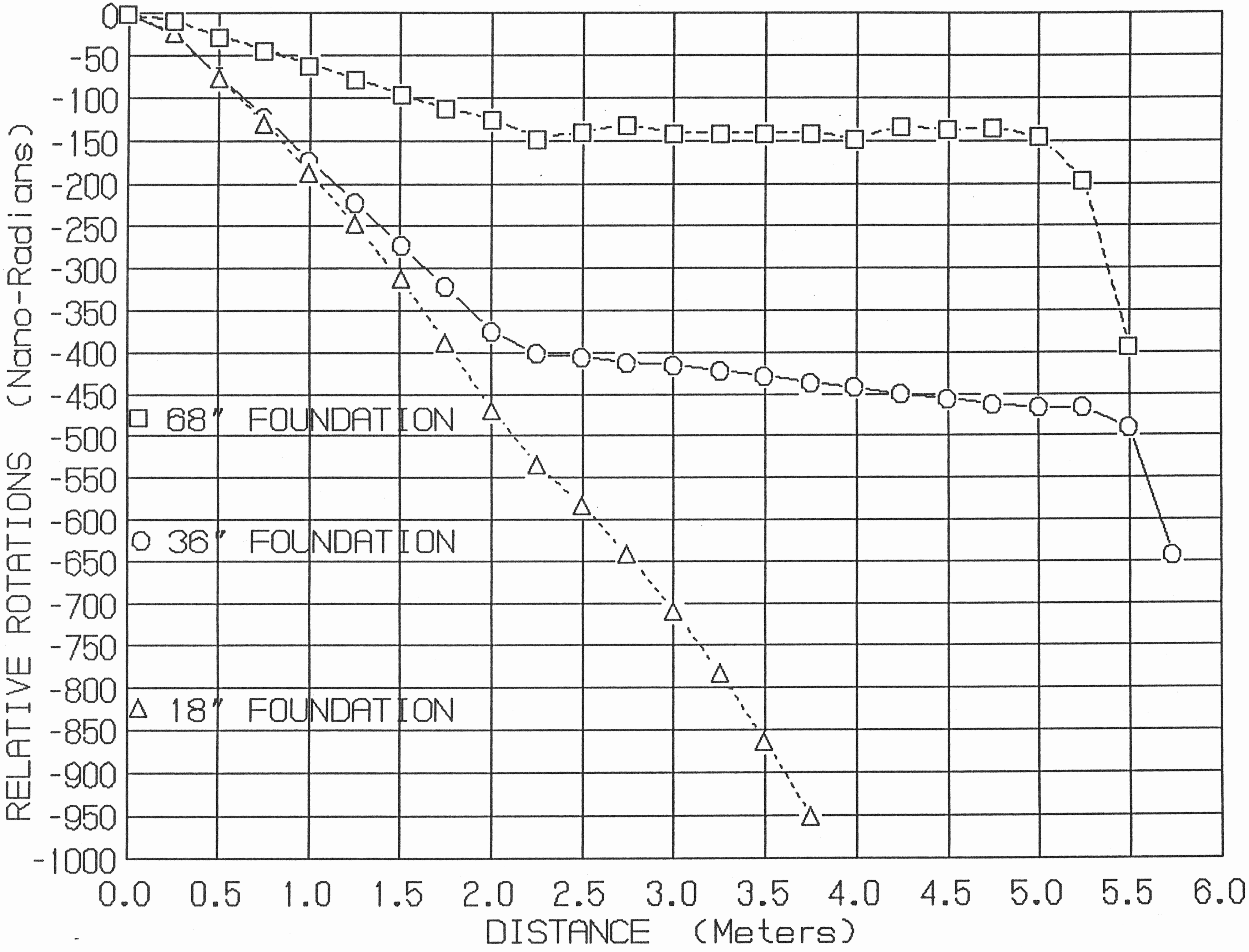
10 MINUTE THERMAL FOUNDATION DEFORMATIONS



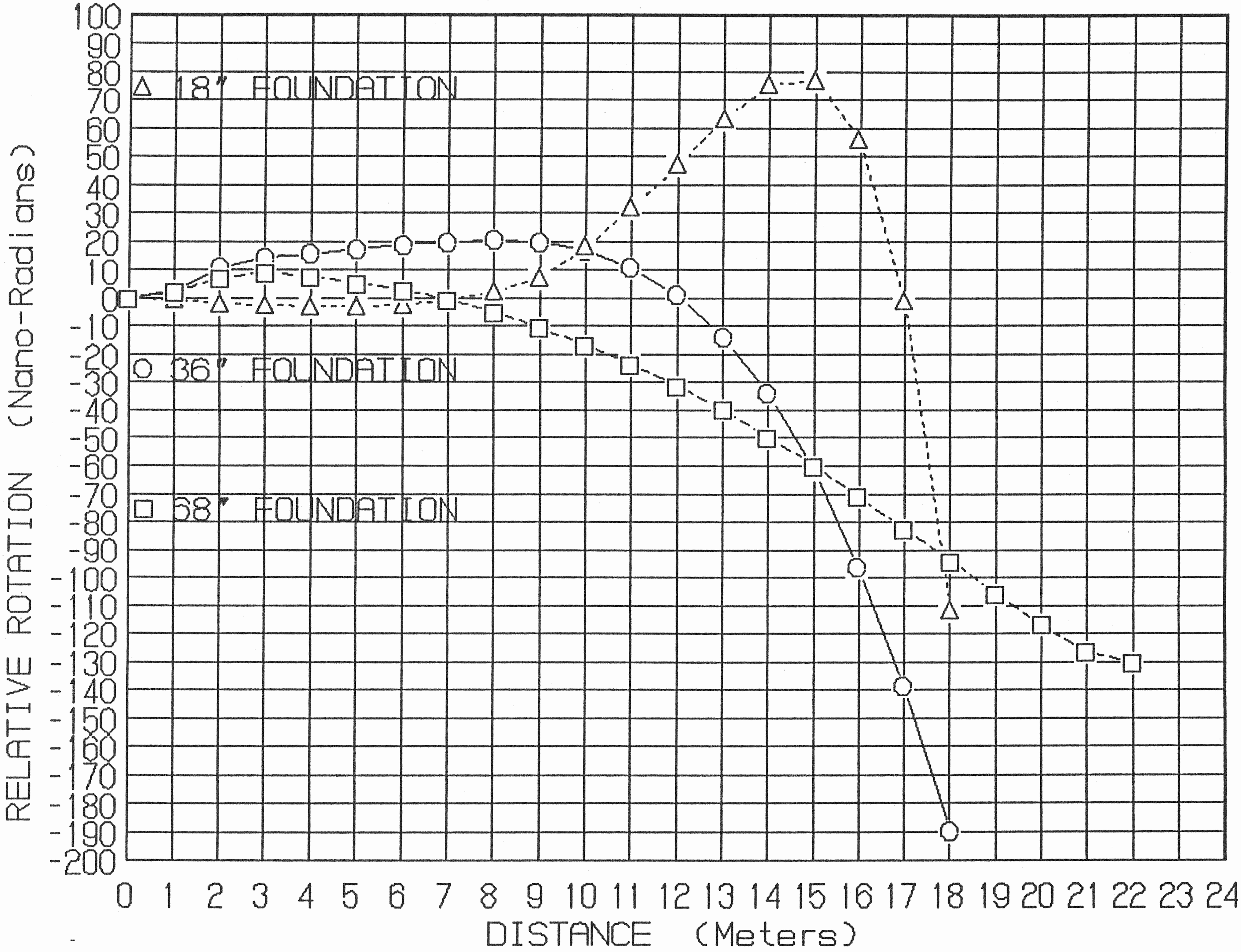
10 MINUTE THERMAL FOUNDATION DEFORMATIONS



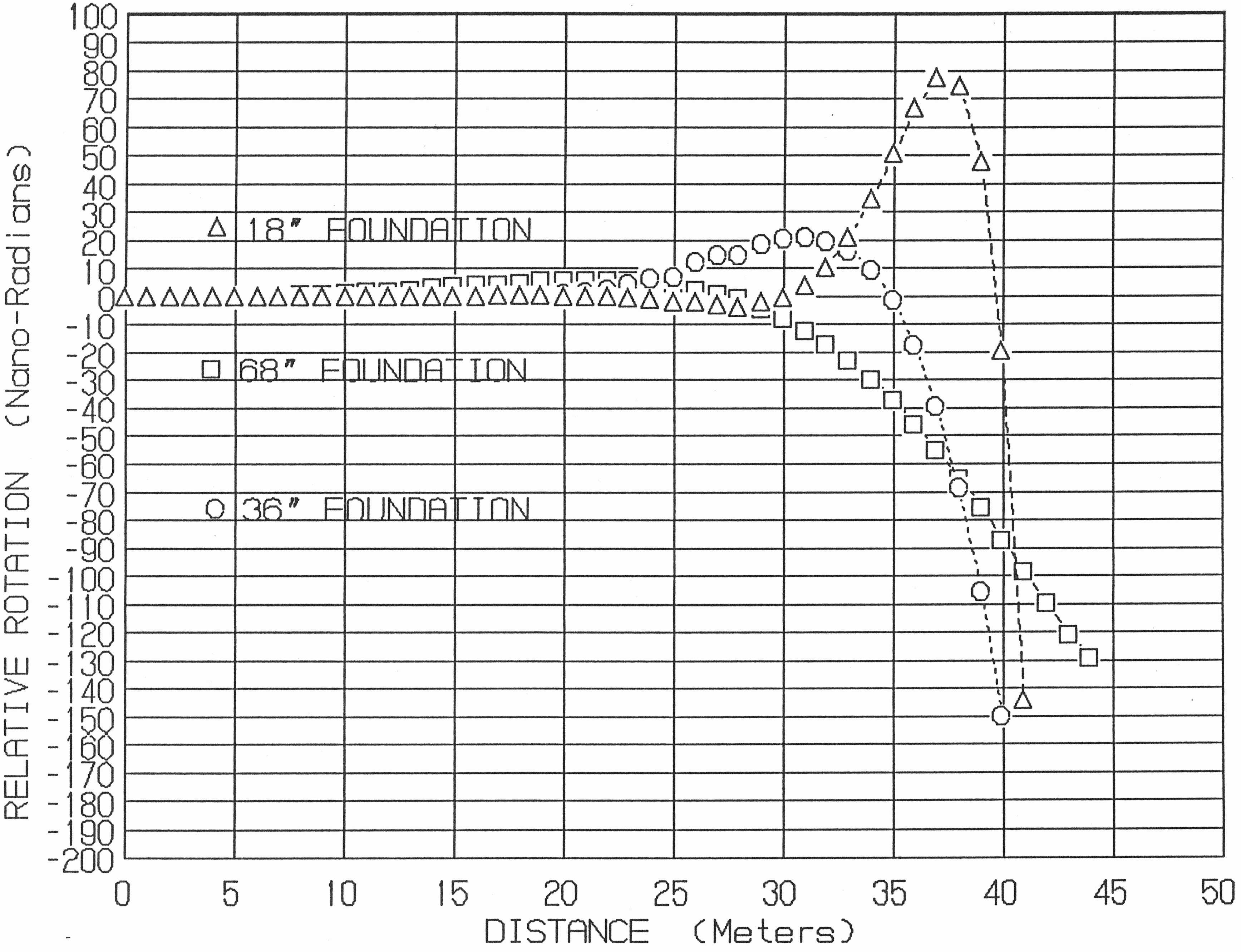
10 MINUTE THERMAL FOUNDATION ROTATIONS



16 MINUTE THERMAL FOUNDATION ROTATIONS



10 MINUTE THERMAL FOUNDATION ROTATIONS



PARSONS

Calculation Sheet

Job Number	Cost Center	Page Number	Sheet of
402117 21013	01-7123		

Rev	Date	By	Ck

Title Thermal Deformations

68" Thick Foundation - 152' Long From ℄

Node (#)	Length (in)	Displacement (1x10^{-3} in)	Rotation (Nano-Radians)	ΔΘ/2 meters (Nano-Radians)
1	0	0.00089555	—	—
11	40	0.00089544	0.003	—
21	80	0.00089561	0.004	0.004
31	120	0.00089745	0.046	0.049
41	160	0.00090329	0.146	0.142
51	200	0.00091635	0.327	0.281
61	240	0.00094078	0.611	0.465
71	280	0.00098163	1.021	0.694
81	320	0.0010449	1.582	0.971
91	360	0.0011372	2.308	1.287
101	400	0.0012664	3.230	1.648
111	440	0.0014407	4.358	2.05
121	480	0.0016691	5.710	2.48
131	520	0.0019611	7.300	2.942
141	560	0.0023263	9.130	3.41
151	600	0.0027747	11.210	3.91
161	640	0.0033156	13.522	4.392
171	680	0.0039580	16.060	4.85
181	720	0.0047097	18.792	5.27
191	760	0.0055766	21.672	5.612
201	800	0.0065625	24.647	5.855
211	840	0.0076681	27.64	5.968
221	880	0.0088900	30.547	5.9
231	920	0.010220	33.25	5.61
241	960	0.011644	35.60	5.053
251	1000	0.013141	37.425	4.175

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Calculation Sheet

Job Number	Cost Center	Page Number	Sheet of
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Title Thermal Deformations

68" Thick Foundation - 152' Long From ℄

Node (#)	Length (in)	Displacement (1×10^{-3} in)	Rotation (Nano-Radians)	ΔΘ/2 meters (Nano-Radians)
261	1040	0.014680	38.475	2.875
271	1080	0.016223	38.575	1.15
281	1120	0.017718	37.375	-0.10
291	1160	0.019102	34.6	-3.975
301	1200	0.020298	29.9	-7.475
311	1240	0.021213	22.875	-11.725
321	1280	0.021740	13.175	-16.725
331	1320	0.021752	0.300	-22.575
341	1360	0.021106	-16.15	-29.325
351	1400	0.019640	-36.65	-36.95
361	1440	0.017176	-61.6	-45.45
371	1480	0.013519	-91.425	-54.775
381	1520	0.0084592	-126.49	-64.89
391	1560	0.0017763	-167.07	-75.645
401	1600	-0.0067571	-213.33	-86.84
411	1640	-0.017370	-265.32	-98.25
421	1680	-0.030284	-322.85	-109.52
431	1720	-0.045708	-385.6	-120.28
441	1760	-0.063778	-451.75	-128.9
451	1800	-0.086741	-574.07	-188.47
457	1824 (152 ft)	-0.10270		

PARSONS **Calculation Sheet**	Job Number	Cost Center	Page Number	Sheet of
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36" Thick Foundation – 152' Long From ℄

Node (#)	Length (in)	Displacement (1×10^{-3} in)	Rotation (Nano-Radians)	ΔΘ/2 meters (Nano-Radians)
261	1040	0.0024153	19.52	12.64
271	1080	0.0034413	25.65	15.26
281	1120	0.0048210	34.49	14.98
291	1160	0.0065963	44.38	18.73
301	1200	0.0087923	54.90	20.41
311	1240	0.011407	65.37	20.99
321	1280	0.014399	74.80	19.90
331	1320	0.017669	81.75	16.38
341	1360	0.021047	84.45	9.65
351	1400	0.024269	80.55	−1.20
361	1440	0.026958	67.23	−17.23
371	1480	0.028605	41.18	−39.38
381	1520	0.028553	−1.30	−68.55
391	1560	0.025986	−64.18	−105.35
401	1600	0.019928	−151.45	−150.15
411	1640	0.0092605	−266.68	−202.51
421	1680	−0.0072458	−412.65	−261.2
431	1720	−0.030867	−590.53	−323.85
441	1760	−0.062832	−799.12	−386.47
451	1800	−0.10405	−1030.4	−439.87
457	1824	−0.13660	−1356.2	−557.08
	(152 ft)			

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Calculation Sheet

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Title Thermal Deformations

36" Thick Foundation - 152' Long From ℄

Node (#)	Length (in)	Displacement (1×10^{-3} in)	Rotation (Nano-Radians)	Δθ/2meters (Nano-Radians)
1	0	0.0019443	—	—
11	40	0.0019449	0.015	—
21	80	0.0019465	0.040	0.04
31	120	0.0019487	0.055	0.04
41	160	0.0019506	0.048	0.01
51	200	0.0019513	0.018	-0.04
61	240	0.0019493	-0.050	-0.10
71	280	0.0019432	-0.153	-0.17
81	320	0.0019311	-0.303	-0.25
91	360	0.0019108	-0.508	-0.36
101	400	0.0018801	-0.768	-0.47
111	440	0.0018367	-1.085	-0.58
121	480	0.0017786	-1.453	-0.64
131	520	0.0017039	-1.868	-0.78
141	560	0.0016117	-2.305	-0.85
151	600	0.0015022	-2.738	-0.87
161	640	0.0013774	-3.120	-0.82
171	680	0.0012418	-3.390	-0.65
181	720	0.0011027	-3.478	-0.36
191	760	0.00097188	-3.271	0.12
201	800	0.00086550	-2.660	0.82
211	840	0.00080555	-1.500	1.77
221	880	0.00082020	0.3663	3.03
231	920	0.00094429	3.102	4.60
241	960	0.0012192	6.873	6.51
251	1000	0.0016347	10.387	7.29

PARSONS Calculation Sheet	Job Number 402117 21013	Cost Center 01-7123	Page Number	Sheet of

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18" Thick Foundation - 152' Long From ℄

Node #	Length (in)	Displacement $(1 \times 10^{-3}$ in)	Rotation (Nano-Radians)	$\Delta\Theta$/2meter (Nano-Radians)
1	0	0.0018401	—	—
11	40	0.0018406	0.013	—
21	80	0.0018418	0.030	0.03
31	120	0.0018432	0.035	0.02
41	160	0.0018446	0.035	0.005
51	200	0.0018458	0.030	-0.005
61	240	0.0018469	0.028	-0.007
71	280	0.0018478	0.023	-0.007
81	320	0.0018486	0.020	-0.008
91	360	0.0018491	0.013	-0.01
101	400	0.0018498	0.018	-0.002
111	440	0.0018505	0.018	0.005
121	480	0.0018517	0.030	0.012
131	520	0.0018535	0.045	0.027
141	560	0.0018565	0.075	0.045
151	600	0.0018612	0.118	0.073
161	640	0.0018682	0.175	0.100
171	680	0.0018781	0.245	0.127
181	720	0.0018909	0.320	0.145
191	760	0.0019062	0.383	0.138
201	800	0.0019222	0.400	0.080
211	840	0.0019355	0.333	-0.050
221	880	0.0019400	0.113	-0.287
231	920	0.0019269	-0.328	-0.661
241	960	0.0018844	-1.063	-1.176
251	1000	0.0017986	-2.145	-1.817

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Calculation Sheet

Job Number	Cost Center	Page Number	Sheet of
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Title Thermal Deformations

18" Thick Foundation - 152' Long From ℄

Node (#)	Length (in)	Displacement (1 x 10^{-3} in)	Rotation (Nano-Radians)	Δθ/2motor (Nano-Radians)
261	1040	0.0016730	-3.140	-2.077
271	1080	0.0014464	-5.665	-3.520
281	1120	0.0011722	-6.855	-3.715
291	1160	0.00085654	-7.892	-2.227
301	1200	0.00055697	-7.489	-0.634
311	1240	0.00038033	-4.416	3.476
321	1280	0.00049658	2.906	10.395
331	1320	0.0011466	16.25	20.666
341	1360	0.0026357	37.23	34.324
351	1400	0.0053022	66.66	50.41
361	1440	0.0094450	103.69	66.46
371	1480	0.015197	143.8	77.14
381	1520	0.022330	178.3	74.61
391	1560	0.029981	191.3	47.50
401	1600	0.036323	158.6	-19.70
411	1640	0.038209	47.15	-144.15
421	1680	0.030889	-183.0	-341.6
431	1720	0.0079373	-573.8	-620.95
441	1760	-0.038366	-1157.5	-974.50
451	1800	-0.11592	-1938.8	-1365.0
457	1824	-0.18170	-1644.5	

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Calculation Sheet

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68" Thick Foundation – 19 ft Long From ℄

Node (FF)	Length (in)	Displacement (1×10^{-3} in)	Rotation (Nano-Radians)	Δθ/Lengths (Nano-Radians)
1	0	0.016571	—	—
21	10	0.016485	-8.60	—
41	20	0.016225	-26.00	—
61	30	0.015792	-43.30	—
81	40	0.015186	-60.60	—
101	50	0.014406	-78.00	—
121	60	0.013453	-95.30	—
141	70	0.012325	-112.8	—
161	80	0.011092	-123.3	-123.3
181	90	0.0095453	-154.7	-146.1
201	100	0.0078925	-165.3	-139.3
221	110	0.0060640	-182.9	-129.6
241	120	-0.0040595	-200.5	-139.9
261	130	-0.0018792	-218.0	-140.0
281	140	-0.00047585	-235.5	-140.2
301	150	-0.0030036	-252.8	-140.0
321	160	-0.0057004	-269.7	-146.4
341	170	-0.0085615	-286.1	-131.4
361	180	-0.011582	-302.1	-136.8
381	190	-0.014763	-318.1	-135.2
401	200	-0.018123	-336.1	-135.6
421	210	-0.021752	-362.9	-144.9
441	220	-0.026066	-431.4	-195.9
451	225	-0.029291	-645.0	-392.2
457	228	-0.033496	-1401.6	-1131.9
	(19ft)			

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Calculation Sheet

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36" Thick Foundation – 19 ft Long From ℄

Node (II)	Length (in)	Displacement (1×10^{-3} in)	Rotation (Nano-Radians)	$\Delta\theta$/2meters (Nano-Radians)
1	0	0.045978	—	—
21	10	0.045733	–24.50	—
41	20	0.044999	–73.40	—
61	30	0.043773	–122.6	—
81	40	0.042052	–172.1	—
101	50	0.039834	–221.8	—
121	60	0.037113	–272.1	—
141	70	0.033885	–322.8	—
161	80	0.030141	–374.4	–374.4
181	90	0.025876	–426.5	–402.0
201	100	0.021081	–479.5	–406.1
221	110	0.015748	–537.3	–410.7
241	120	0.009867	–588.1	–416.0
261	130	0.003430	–643.7	–421.9
281	140	–0.003574	–700.4	–428.3
301	150	–0.011154	–758.0	–435.2
321	160	–0.019320	–816.6	–442.2
341	170	–0.028081	–876.1	–449.6
361	180	–0.037442	–936.1	–456.6
381	190	–0.047400	–995.8	–462.5
401	200	–0.057934	–1053.4	–465.3
421	210	–0.069031	–1109.7	–466.0
441	220	–0.080935	–1190.4	–490.0
451	225	–0.087940	–1401.0	–643.0
457	228 (19 ft)	–0.094404	–2154.6	

PARSONS

Calculation Sheet

	Job Number	Cost Center	Page Number	Sheet of
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Title Thermal Deformations

18" Thick Foundation – 19 ft Long From ℄

Node (#)	Length (in)	Displacement (1×10^{-3} in)	Rotation (Nano-Radians)	$\Delta\Theta$/2 meters (Nano-Radians)
1	0	0.071764	—	—
21	10	0.071511	-25.30	—
41	20	0.070744	-76.70	—
61	30	0.069445	-129.90	—
81	40	0.067579	-186.60	—
101	50	0.065103	-247.60	—
121	60	0.061959	-314.40	—
141	70	0.058078	-388.10	—
161	80	0.053379	-469.90	-469.9
181	90	0.047772	-560.70	-535.4
201	100	0.041157	-661.50	-584.8
221	110	0.033424	-773.30	-643.4
241	120	0.024457	-896.70	-710.1
261	130	0.014133	-1032.40	-784.8
281	140	0.002325	-1180.7	-866.3
301	150	-0.011095	-1342.0	-953.9
321	160	-0.026259	-1516.4	-1046.5
341	170	-0.043293	-1703.4	-1142.7
361	180	-0.062321	-1902.8	-1241.3
381	190	-0.083457	-2113.6	-1340.3
401	200	-0.10681	-2335.3	-1438.6
421	210	-0.13243	-2562.0	-1529.6
441	220	-0.16027	-2784.0	-1603.3
451	225	-0.17544	-3034.0	
457	228	-0.18677	-3776.6	

(19 ft)

PARSONS **Calculation Sheet**	Job Number	Cost Center	Page Number	Sheet of
	462111 21013	01-7123		

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68" Thick Foundation - 76' Long From ℄

Node	Length(in)	Displacement(10^{-3}in)	(Nano-Radians) Rotation	(Nano-Radians) $\Delta\theta$/2 meters
1	0	0.017688	—	—
21	40	0.017787	2.48	—
41	80	0.018078	7.28	7.28
61	120	0.018540	11.55	9.07
81	160	0.019137	14.93	7.65
101	200	0.019821	17.10	5.55
121	240	0.020526	17.63	2.70
141	280	0.021175	16.23	- 0.87
161	320	0.021670	12.38	- 5.25
181	360	0.021898	5.70	- 10.53
201	400	0.021728	- 4.25	- 16.63
221	440	0.021014	- 17.85	- 23.55
241	480	0.019587	- 35.68	- 31.43
261	520	0.017266	- 58.03	- 40.18
281	560	0.013851	- 85.38	- 49.70
301	600	0.009128	- 118.08	- 60.05
321	640	0.002872	- 156.39	- 71.01
341	680	- 0.005149	- 200.52	- 82.44
361	720	- 0.015170	- 250.51	- 94.12
381	760	- 0.027421	- 306.27	- 105.75
401	800	- 0.042119	- 367.45	- 116.94
421	840	- 0.059431	- 432.80	- 126.53
441	880	- 0.079345	- 497.85	- 130.40
451	900	- 0.090654	- 565.45	- 176.87
457	912 (76 ft)	- 0.102110	- 954.66	- 579.84

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Calculation Sheet

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Title Thermal Deformations

36" Thick Foundation – 76' Long From ℄

Node (#)	Length (in)	Displacement (1×10^{-3} in)	Rotation (Nano-Radians)	Δθ/2 meter
1	0	-0.00007077	—	—
21	40	0.00006914	3.50	—
41	80	0.00049517	10.65	10.65
61	120	0.0012251	18.25	14.75
81	160	0.0022855	26.51	15.86
101	200	0.0037078	35.56	17.31
121	240	0.0055215	45.34	18.83
141	280	0.0077464	55.62	20.06
161	320	0.010381	65.87	20.53
181	360	0.013392	75.28	19.66
201	400	0.016693	82.53	16.66
221	440	0.020134	86.03	10.75
241	480	0.023476	83.55	1.02
261	520	0.026374	72.45	-13.61
281	560	0.028354	49.50	-34.05
301	600	0.028799	11.13	-61.32
321	640	0.026934	-46.63	-96.13
341	680	0.021823	-127.77	-138.90
361	720	0.012383	-236.00	-189.37
381	760	-0.002592	-374.37	-246.60
401	800	-0.024373	-544.52	-308.52
421	840	-0.054209	-745.90	-371.53
441	880	-0.093146	-973.42	-428.90
451	900	-0.11612	-1031.8	-381.2
457	912 (76 ft)	-0.13469	-1117.7	-413.1

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Title Thermal Deformations

18" Thick Foundation - 76' Long From ℄

Node (#)	Length (in)	Displacement (1×10^{-3} in)	Rotation (Nano-Radian)	$\Delta\Theta$/2 meters (Nano-Radian)
1	0	0.0020419	—	—
21	40	0.0020156	- 0.66	—
41	80	0.0019340	- 2.04	- 2.0
61	120	0.0017909	- 3.58	- 2.9
81	160	0.0015805	- 5.26	- 3.2
101	200	0.0013046	- 6.90	- 3.3
121	240	0.0009822	- 8.06	- 2.8
141	280	0.0006629	- 7.98	- 1.1
161	320	0.0004415	- 5.54	2.5
181	360	0.0004730	0.79	7.2
201	400	0.0009825	12.74	18.3
221	440	0.0022628	32.01	32.1
241	480	0.0046486	59.65	46.9
261	520	0.0084556	95.18	63.2
281	560	0.013865	135.23	75.6
301	600	0.020746	172.02	76.8
321	640	0.028395	191.22	56.0
341	680	0.035220	170.62	- 1.4
361	720	0.038384	79.10	- 112.1
381	760	0.033493	- 122.27	- 292.9
401	800	0.014467	- 475.65	- 554.8
421	840	- 0.026198	- 1016.60	- 894.3
441	880	- 0.096503	- 1750.00	- 1274.4
451	900	- 0.14484	- 1977.3	
457	912 (76 ft)	- 0.18059	- 2144.3	

Parsons-LIGO
Facility Designer and Construction Manager

Interoffice Correspondence

IOC # MU-951114-0

To Tim Melott
Date 14-Nov-95
From Atia Y. Atia
Phone x-4573
Location T-669
SUBJECT Temperature Profile in the LVEA

The following table represent the expected temperature profile inside the LVEA room at the corner station measured in ° F. Interpolation between the given times and the months to calculate the room temperature for missing times and months is valid. Temperatures computed based on the assumptions listed below the table.

July	0700	70.9	71.0	71.0	70.9	71.0
July	0800	71.6	71.7	71.7	71.6	71.7
Month	Time	Area 1	Area 2	Area 3	Area 4	Area 5
Jan.	0000	70.0	70.2	70.2	70.0	70.2
Jan.	0300	70.0	70.0	70.0	70.0	70.0
Jan.	0600	70.0	70.0	70.0	70.0	70.0
Jan.	0900	70.1	70.2	70.2	70.1	70.2
Jan.	1200	70.3	70.4	70.4	70.3	70.4
Jan.	1500	70.3	70.4	70.4	70.3	70.4
Jan.	1800	70.2	70.3	70.3	70.2	70.3
Jan.	2100	70.1	70.3	70.3	70.1	70.3
July	0000	71.0	71.2	71.2	71.0	71.2
July	0300	70.9	71.0	71.0	70.9	71.0
July	0600	70.8	71.0	71.0	70.8	71.0
July	0900	73.0	73.0	73.0	73.0	73.0
July	1200	73.6	73.6	73.6	73.6	73.6
July	1500	74.0	74.0	74.0	74.0	74.0
July	1800	72.0	72.4	72.4	72.0	72.4
July	2100	71.5	71.6	71.6	71.5	71.6
July	1600	73.2	73.0	73.0	73.2	73.0
July	1700	72.9	72.7	72.7	72.7	72.7

Assumptions

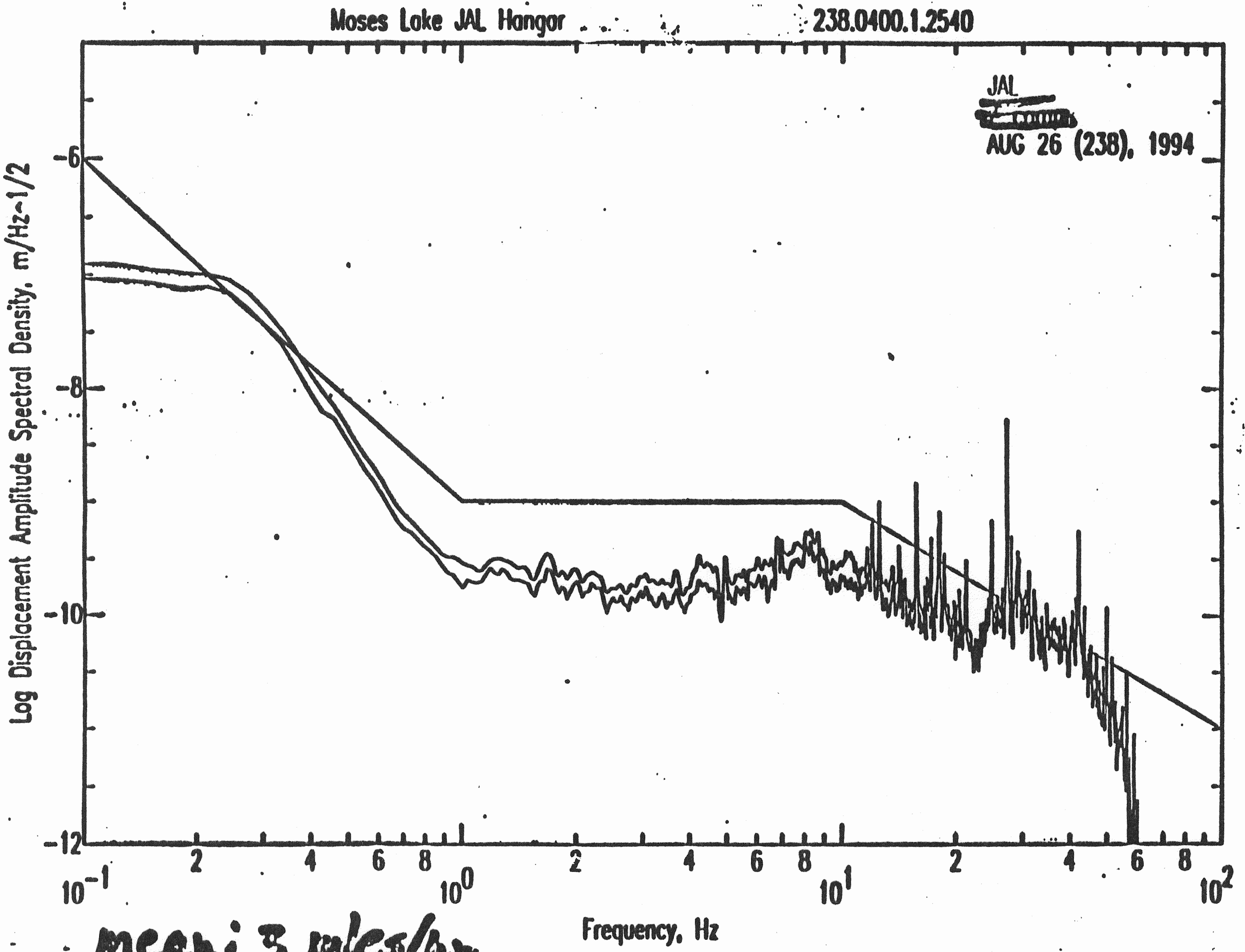
1. Temperature controls shall be proportional type.
2. Room temperature shall be proportional to the room sensible heat gain or loss.
3. Room temperature shall be measured @ 2 feet above the floor level.
4. Clear outdoor conditions, no rains or clouds.
5. Steady internal heat gain from equipment & lights.
6. No sudden weather conditions change.
7. Room temperature will be controlled within +/- 2 °F
8. SCR controls on the electric duct heaters.

7. Wind Induced Vibrations

The wind induced vibrations at the Moses Lake JAL Hanger were measured at light wind conditions and at wind speeds above 20 miles per hour. The measured PSD spectra of the vibrations on the hanger foundation are included at the end of this section. Based on these measurements at the JAL building that is a facility not far from the Hanford site with similar deep alluvial sandy soil supporting the foundation, it appears that the ambient PSD measurements for this hanger foundation indicate that the ground motions expected at the LIGO facilities should be acceptable for wind speeds up to 20 mph.

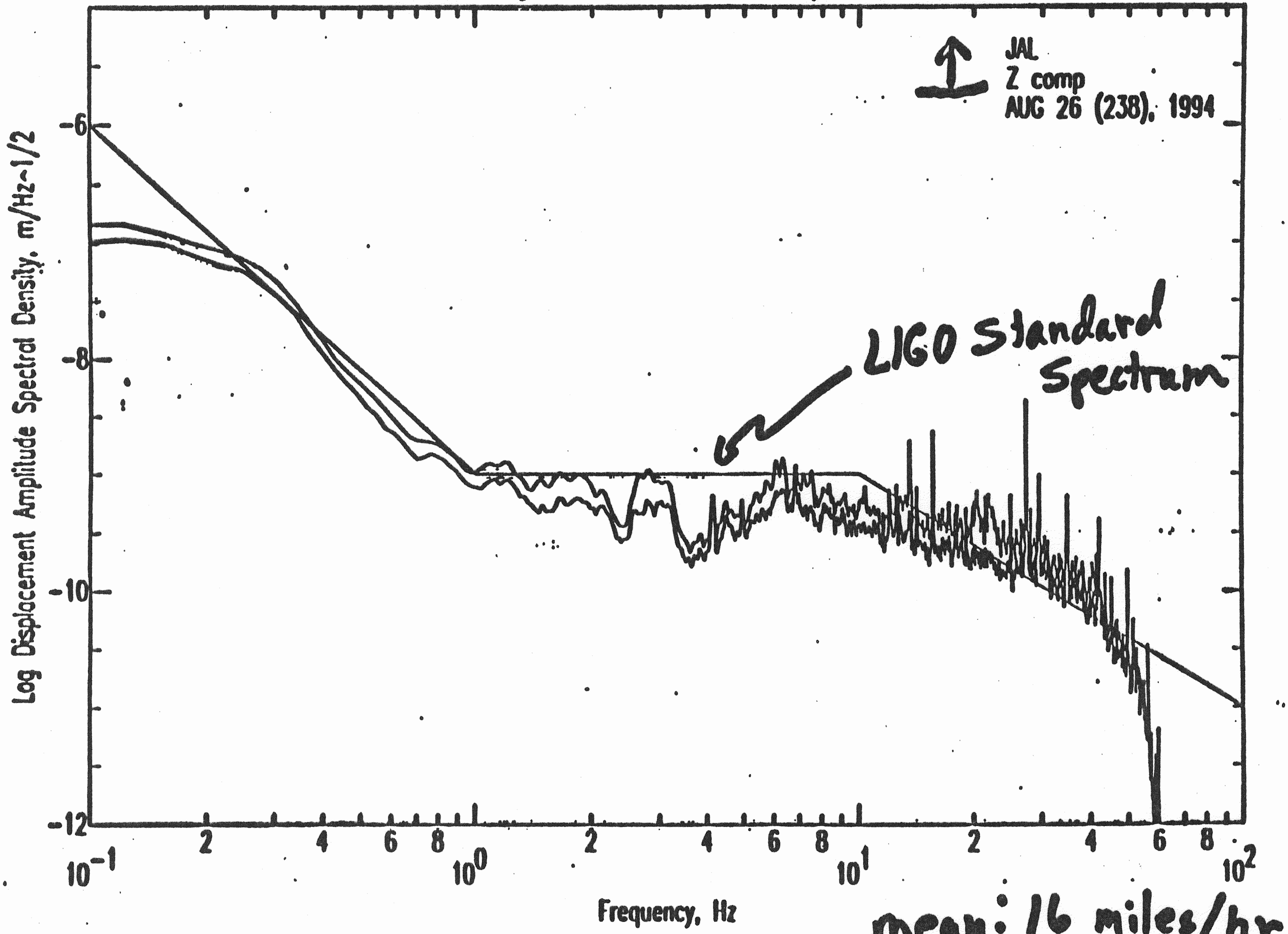
Various analytical methods have been applied to attempt to estimate the amount of wind induced vibrations in the LIGO structures. Several inconsistencies have been discovered between the assumptions used to describe the structural properties of the LIGO facilities in the hand calculated estimates of the wind induced vibrations. Therefore there does not appear to be a reliable calculation available at this time to determine the wind induced buffeting response of the LIGO structures. Other research is in progress to attempt to estimate the wind induced motions of the LIGO structures and further analyses may provide estimates of the wind induced vibrations. As the final design of the LIGO building structures develop, reliable finite element analyses of the structures can be made. It will become possible to accurately determine the building displacement for various wind speeds. A reasonable method of estimating the building motions might be to estimate the fraction of the static displacement calculated from wind drag forces at various wind speeds. If this were combined with more realistic estimates of the building modal frequencies an estimate of the wind induced vibrations might be made.

However, based on the measured data at Moses Lake it appears that wind speeds under 20 mph to 30 mph should not produce unacceptable vibrations on the technical foundations of the LIGO facilities. The technical foundations are being separated from the foundations supporting the exterior building structure. At the Moses Lake facility the hanger foundation was continuous with the exterior building structure without a separation joint. The wind data obtained for the Hanford site and the Livingston site indicate that there is a very small probability of exceeding 30 mph at either site. At the Hanford site the annual wind speed exceedence probability is 35% for 10 mph, 4% for 20 mph, and 0.5% for 30 mph. At the Livingston site the annual wind speed exceedence probability is 28% for 10 mph, 1% for 20 mph, and 0.1% for 30 mph. These wind speed exceedence data indicate that 95% of the time at either site it can be expected that the wind will be less than 20 mph. Using the Moses Lake data as a reference it appears that wind induced vibrations will not produce excessive foundation vibrations on the technical foundations since the LIGO criteria requires that external natural phenomenon such as wind should not produce excessive vibrations more than 5% of the time.



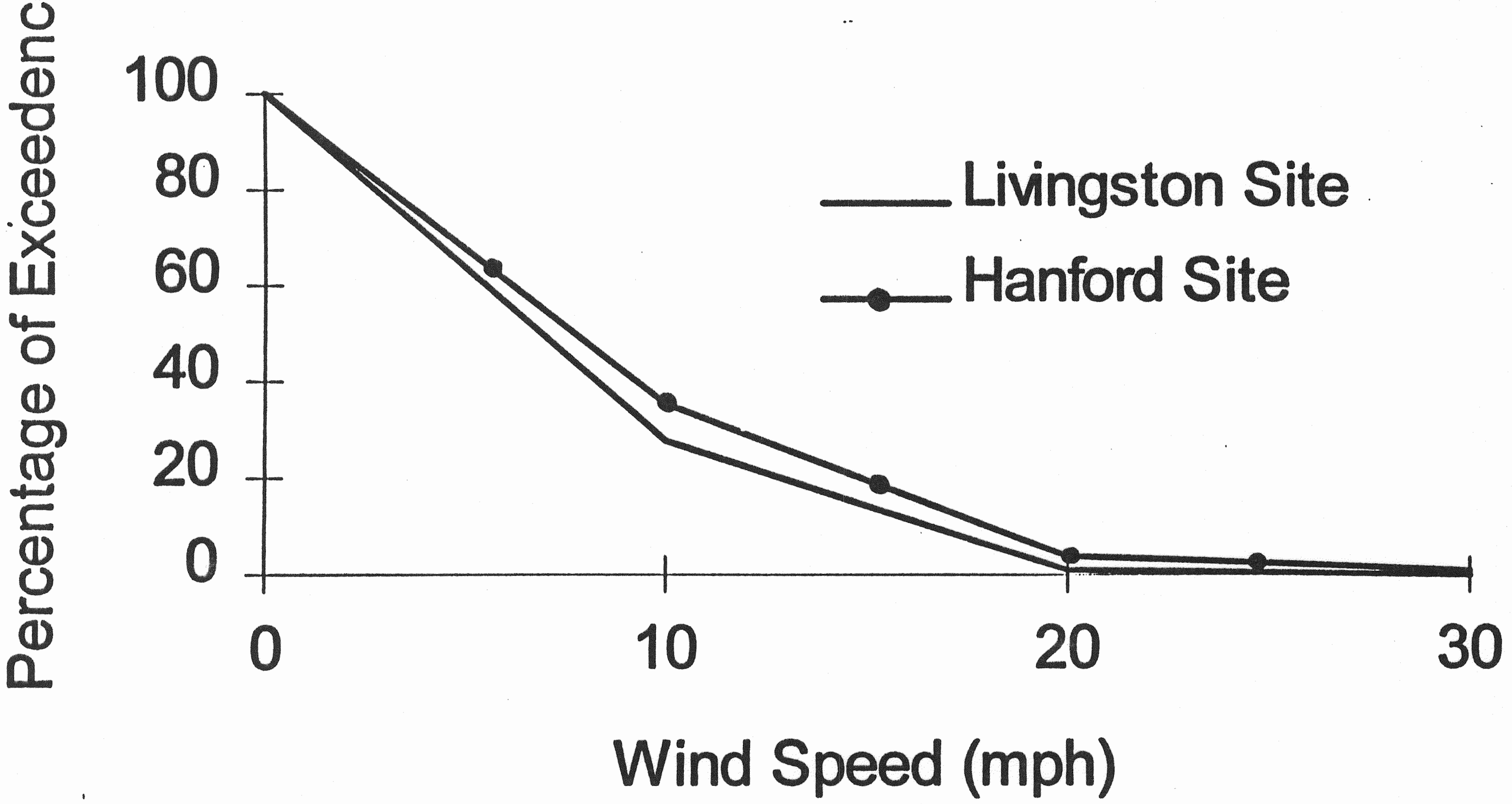
mean: 3 miles/hr
peak: 3 miles/hr

Moses Lake JAL Hangar Moderate Wind 7 - 8 m/s 238.0100.1.2000



mean: 16 miles/hr
peak: 22 miles/hr

Wind Speed Exceedence



8. HVAC Equipment Vibrations

The HVAC equipment vibration predictions are based on 5 Hz isolation systems supporting the HVAC fan skids. The analyses are based on the fans operating at 1800 rpm (30 Hz). An unbalanced force equal to 0.1g times the rotor weight of the fans is used to provide an upper bound to the unbalanced vibrations produced by the fan rotors. It is expected that the acceptance level of unbalanced force will be approximately 1/4 of this extreme force. The reason for using this conservative estimate of the forcing function is to allow for normal wear so that excessive maintenance on the fans would not be required. It is expected that an annual maintenance inspection and cleaning of the fans would be sufficient to keep the fans operating within this vibration range.

For the corner station mechanical room, it was assumed that six fans were operating simultaneously and that the unbalanced forces from each fan were in phase. A finite element model of the concrete structure supporting the six fans in the mechanical room was made and a steady-state solution was obtained at the two foot thick concrete foundation supported on soil stiffnesses for the fan support structure. The results presented at the PDR were based on the maximum vertical responses of the concrete foundation that occurred at the corners of the HVAC foundation. However, it was discovered that incorrect damping values had been in used in the analyses. The analyses were rerun with the correct damping values and the following displacements were obtained the fan building foundation. In the transverse horizontal direction the displacement of the fan building foundation was $1.63X10^{-8}$ m. In the longitudinal horizontal direction, parallel to the axes of the fans, the displacement of the fan building foundation was $0.59X10^{-8}$ m. In the vertical direction the displacement of the fan building foundation was $3.62X10^{-8}$ m. The estimates of the displacements at the critical vacuum equipment on the LVEA technical foundation were made by attenuating the ground surface vibrations emanating from the fan support foundation to the location of the vacuum equipment. This attenuation between the fan support foundation and the vacuum equipment location was found to be equal to a multiplication factor of 0.42. Thus the estimated LVEA foundation vibration was $1.5X10^{-8}$ m versus a spike criteria amplitude of $1.4X10^{-8}$ m at 30 Hz. This amplitude estimate did not consider the effect of averaging the fan foundation motions which could reduce the vibrations by a multiplication factor of 1/4 or 1/5. Also this amplitude estimate did not include the reductions associated with moving the relatively rigid and massive LVEA concrete foundation on top of the ground which could reduce the vibrations by a multiplication factor of 1/4 or 1/5. Thus it was expected that the actual spike amplitude measured on the LVEA foundation slab near any of the critical vacuum components would be less than the spike amplitude defined by the criteria at 30 Hz.

Similar analyses were conducted for the Mid Station and End Station where only one fan operates at a time. There are two fans located at each of these stations but one fan is expected to be on standby. The concrete fan support structure is located in the mechanical rooms at these stations and is similarly separated from the surrounding structure. The maximum vertical displacements at the corner of the fan foundation slab were calculated using a finite element model of the concrete fan support structure resting on the soil stiffnesses. The maximum foundation responses were attenuated based on the separation distance between the critical vacuum equipment location and the foundation slab. The resulting peak amplitude at the fan building for the Mid and End Stations was $1.4X10^{-8}$ m. At the vacuum equipment location the ground motion vibration would be attenuated by a factor of 0.3 so that the vertical ground motion would be $0.42X10^{-8}$ m. The spike amplitude criteria displacement limit is $1.4X10^{-8}$ m. As noted before, it is expected that the average fan foundation motion is about 1/4 of the peak fan foundation motion and an additional attenuation by a multiplication factor of 1/4 could be expected for the vibration reduction expected for the effect of the ground motion forcing the motion of the technical foundations at the Mid Stations and End Stations. Thus it is expected that the spike amplitude criteria will be satisfied for the HVAC fan vibration sources when all of these effects are considered. Note that the specifications for balancing the HVAC fans and isolating the fan vibrations will require the fan fabricators to provide equipment that will have vibrations that are reduced by a multiplication factor of 1/4. If further reductions are needed in the future it will also be possible to upgrade the fan isolation system so that the unbalanced fan forces applied to the fan foundations are reduced. It is not considered to be necessary at this time to provide a significantly more sophisticated fan isolation system but the isolation system could be upgraded in the future if desired.

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Calculation Sheet

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Title LVEA – HVAC Analysis

The soil properties are:

$G_s = 17{,}937$ psi

$\nu_s = 0.37$

$\gamma_s = 105$ lb/ft^3

The area of the LVEA-HVAC concrete fan room is

$A = 330{,}336$ in^2

From Richart, Hall, + Woods, the vertical soil stiffness is given as:

$$K_V = \frac{G_s}{1-\nu}\beta_z\sqrt{A} \quad , \quad \beta_z = 2.15$$

$$K_V = \left(\frac{17{,}937}{1-0.37}\right)(2.15)\sqrt{330{,}336} = 35{,}182{,}417 \text{ lb/in}$$

and the horizontal soil stiffness is:

$$K_H = 2(1+\nu)G_s\beta_x\sqrt{A} \quad , \quad \beta_x = 0.97$$

$$K_H = 2(1.37)(17{,}937)(0.97)\sqrt{330{,}336} = 27{,}399{,}968 \text{ lb/in}$$

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There are 246 soil nodes in the finite element model, the area of the equivalent soil beam is:

$$A_{SB} = \frac{330{,}336}{246} = 1343 \text{ in}^2$$

The vertical stiffness of the soil beam is

$$K_{SBV} = \frac{A_{SB} E_{SB}}{l_{SB}}$$

The arbitrary length of the soil beam is 68", and the total soil stiffness is known, therefore the Young's Modulus of the soil beam can be determined.

$$E_{SB} = \frac{(35{,}182{,}417)(68)}{(330{,}336)} = 7242 \text{ psi}$$

The soil beams are fixed at their base and at the end connected to the concrete foundation, so the lateral stiffness of the soil beam is,

$$K_{SBH} = \frac{12 E_{SB} I_{SB}}{l_{SB}^3} = \frac{27{,}399{,}968}{246}$$

Solving for the area moment of inertia of the soil beam, I_{SB} is

$$I_{SB} = \frac{(27{,}399{,}968)(68)^3}{(246)(12)(7242)} = 402{,}991 \text{ in}^4$$

PARSONS **Calculation Sheet**	Job Number 402117 21013	Cost Center 01-7123	Page Number 3	Sheet of

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HVAC Equipment (1800 rpm)

AHU-3 Air Handler Fan (TWO Required)

W_{R3} = Rotating Weight = 550 lb

W_{T3} = Total Weight = 850 lb

Isolation Frequency = 5 Hz (Vertical + Horizontal)

$f = 5\,Hz = \frac{1}{2\pi}\sqrt{\frac{Kg}{W}}$, $K = \frac{AE}{l}$, Vertical

$l = 30''$, distance from fan support to fan Cg.

Let $E_{fb} = 1000$ psi, then compute the area of the cantilever beam supporting the fan at 5 Hz. $g = 386.4$ in/sec^2

$$\frac{(10\pi)^2(30)(850)}{(1000)(386.4)} = A_{fb} = 65.133\ in^2$$

For the cantilever frequency of 5 Hz

$f = 5\,Hz = \frac{1}{2\pi}\sqrt{\frac{Kg}{W}}$, $K = \frac{3EI}{l^3}$, horizontal

Solving for I,

$$I = \frac{(10\pi)^2(850)(30)^3}{(3)(1000)(386.4)} = 19{,}540\ in^4$$

Note, the unbalanced vibrating force is

$F_{UF} = (0.1g)(550\,lb) = 55\,lb$ @ 30 Hz

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Calculation Sheet

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AHU-2 Air Handler Fan (Two Required)

W_{R2} = Rotating Weight = 750 lb

W_{T2} = Total Weight = 1150 lb

Isolation frequency = 5 Hz (Vertical + Horizontal)

$f = 5\,Hz = \frac{1}{2\pi}\sqrt{\frac{Kg}{W}}$, $K = \frac{AE}{l}$, Vertical

$l = 30''$, distance from fan support to fan Cg.

Let E_{fb} = 1000 psi, then compute area of the fan support beam.

$$\frac{(10\pi)^2(30)(1150)}{(1000)(386.4)} = A_{fb} = 88.121\ in^2$$

For the cantilever frequency of 5 Hz

$f = 5\,Hz = \frac{1}{2\pi}\sqrt{\frac{Kg}{W}}$, $K = \frac{3EI}{l^3}$, horizontal

Solving for I

$$I = \frac{(10\pi)^2(30)^3(1150)}{(3)(1000)(386.4)} = 26,436\ in^4$$

Note the unbalanced vibrating force is

$$F_{UF} = (0.1g)(750\,lb) = 75\,lb \text{ @ } 30\,Hz$$

Also, note AHU-2 and AHU-1 are identical

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Calculation Sheet

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AC-1 : Air Compressor on roof of concrete fan building, @ 3010 rpm (50 Hz)

W_{RAC} = Rotating Weight = 90lb

W_{RACT} = Total Weight = 800lb

Isolation frequency = 5 Hz (Vertical + Horizontal)

$f = 5\,Hz = \frac{1}{2\pi}\sqrt{\frac{Kg}{W}}$, $K = \frac{AE}{l}$, Vertical

$l = 30''$, distance from compressor support to compressor Cg.

Let $E_{cb} = 1000$ psi, then compute the area of the compressor support beam.

$$\frac{(10\pi)^2(30)(800)}{(1000)(386.4)} = A_{cb} = 61.302\,in^2$$

For the cantilever frequency of 5 Hz

$f = 5\,Hz = \frac{1}{2\pi}\sqrt{\frac{Kg}{W}}$, $K = \frac{3EI}{l^3}$, horizontal

solving for I

$$I = \frac{(10\pi)^2(30)^3(800)}{(3)(1000)(386.4)} = 18{,}390\,in^4$$

Note only one forcing frequency can be selected in a given steady-state analysis so the 9lb forcing function @ 50 Hz was ignored. However, the isolated equipment was modeled in the finite element program.

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The plan area of the HVAC concrete housing is,

$A_H = 330,336 \, in^2$, $r_o = \sqrt{\frac{A_H}{\pi}} = 324.27 \, in$

The weight of the HVAC concrete housing is, using a concrete density of $154 \, lb/ft^3$

Floor (24" Thick), $W_F = \left(\frac{24 \times 330,336 \times 154}{1728}\right) = 706,552 \, lb$

Roof (8" Thick), $W_R = \left(\frac{8 \times 330336 \times 154}{1728}\right) = 235,517 \, lb$

Walls (8" Thick), $W_W = \left(\frac{8 \times 545,904 \times 154}{1728}\right) = 389,209 \, lb$

Total Weight $= 1.331273 \times 10^6 \, lb$

From Richart, Hall, & Woods, Page 382

Vertical Damping

$$B_z = \frac{(1-\nu)(m)}{4 \rho_o r_o^3} = \frac{(1-0.37)(1.331273 \times 10^6 / g)}{(4)\left(\frac{105 \, lb/ft^3}{1728 \times g}\right)(324.27)^3} = 0.1012$$

$$D_z = \frac{0.425}{\sqrt{B_z}} = \frac{0.425}{\sqrt{0.1012}} = 1.336$$

Horizontal Damping

$$B_H = \frac{(7-8\nu)(m)}{32(1-\nu)\rho_o r_o^3} = \frac{(7-8 \times 0.37)(1.331273 \times 10^6 / g)}{(32)(1-0.37)\left(\frac{105}{1728 \times g}\right)(324.27)^3} = 0.12876$$

$$D_H = \frac{0.288}{\sqrt{B_H}} = \frac{0.288}{\sqrt{0.12876}} = 0.8026$$

Use 80% of Critical Damping

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Wall Weight (8.5 ft high) Volume (ft³)

① 45 × 8.5 × 8/12 = 255.0

② 45 × 8.5 × 8/12 = 255.0

③ 8 × 8.5 × 8/12 = 45.3

④ 8 × 8.5 × 8/12 = 45.3

⑤ 46 × 8.5 × 8/12 = 260.7

⑥ 32 × 8.5 × 8/12 = 181.3

⑦ 14 × 8.5 × 8/12 = 79.3

⑧ 52 × 8.5 × 8/12 = 294.7

⑨ 32 × 8.5 × 8/12 = 181.3

⑩ 32 × 8.5 × 8/12 = 181.3

⑪ 40 × 8.5 × 8/12 = 226.7

⑫ 40 × 8.5 × 8/12 = 226.7

⑬ 52 × 8.5 × 8/12 = 294.7

3791 ft² 2,527.3 ft³

$2527.3 \times 154\ \text{lb}/\text{ft}^3 = 389,204$

PARSONS Calculation Sheet	Job Number 402117 21013	Cost Center 01-7123	Page Number	Sheet of

Rev	Date	By	Ck	Title LVEA - HVAC Analysis

Nodes

1-246	Foundation, 24" thick
247-492	Roof
493-499	Fan Equipment
500-745	Soil

Elements

1-213	Foundation, 24" Thick	Plate Elements
214-426	Roof, 8" thick	
427-508	East-West Walls, 8" thick	
509-562	North-South Walls, 8" thick	
563-569	Equipment	Beam Elements For Fan Isolation Representation
570-815	Soils	Beam Elements Fos Soil Support Stiffnesses, vertical and Horizontal.

Concrete Properties

$E_c = 3.6\times10^6$ psi (4000 psi strength)

$\nu_c = 0.15$, Poisson's Ratio

$\gamma_c = 154$ lb/ft^3, weight density,

PARSONS Calculation Sheet	Job Number 402117 21013	Cost Center 01-7123	Page Number	Sheet of

Rev	Date	By	Ck	Title LVEA - HVAC Analysis

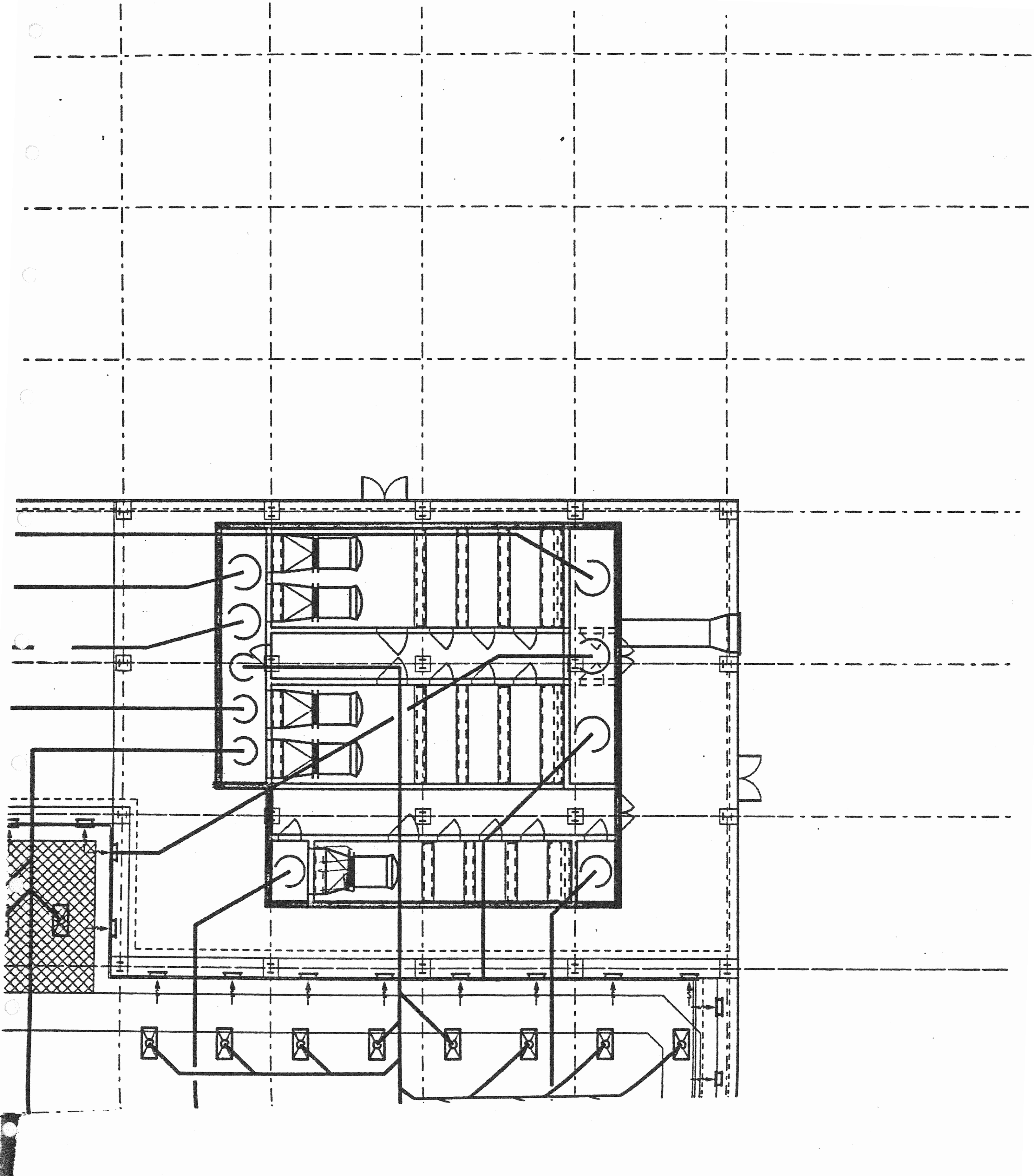
Based on the final analyses of the HVAC Concrete fan building at the LVEA, the following displacements at the fan building foundation were computed. Note that these values were corrected from the values presented at the PDR, the large soil damping values had been inadvertently applied to the equipment isolation modes instead of the rigid body foundation modes of the building. Thus, excessive force was applied to the fan building.

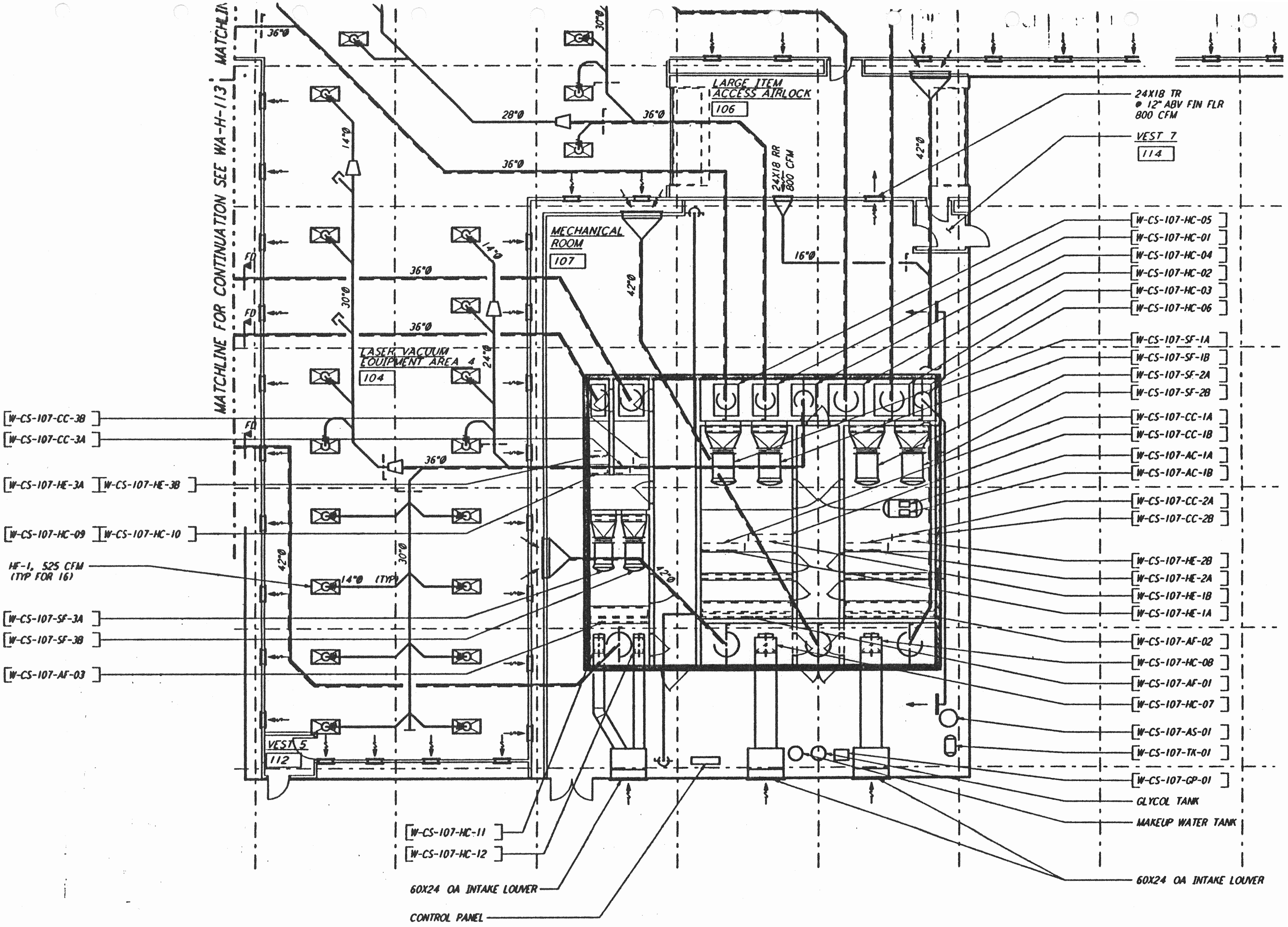
X direction (Horizontal) (Transverse) $= 0.642374 \times 10^{-6}$ in $= 1.63 \times 10^{-8}$ m

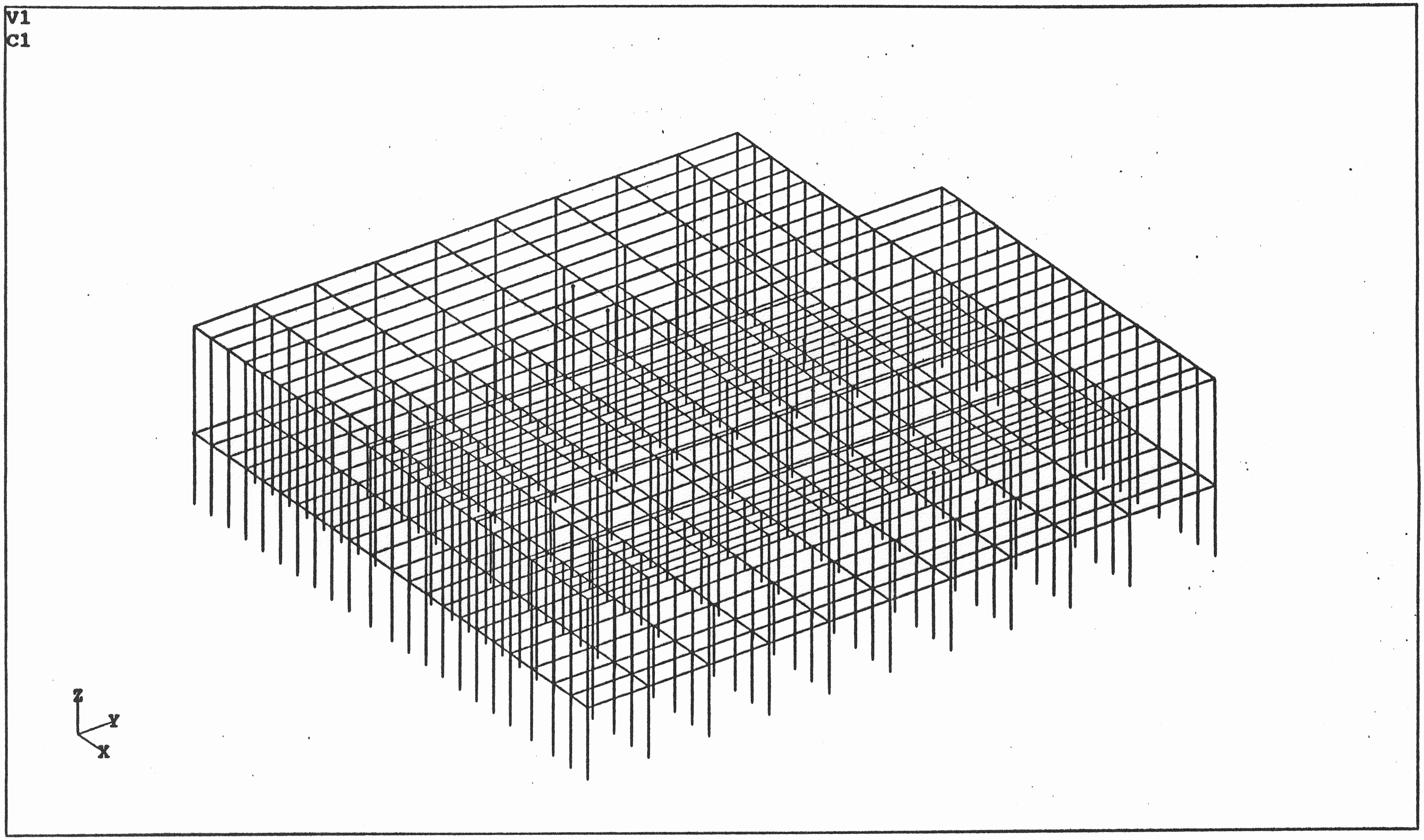
Y direction (Horizontal) (Longitudinal) $= 0.231839 \times 10^{-6}$ in $= 0.589 \times 10^{-8}$ m

Z direction (Vertical) $= 1.42532 \times 10^{-6}$ in $= 3.62 \times 10^{-8}$ m

Note $r_0 = 324.27$ in ≈ 27 ft, and it is about 57 ft to the critical vacuum equipment from the center of the fan building. Thus $\frac{R}{r_0} = \frac{57}{27} \cong 2.1$ and the attenuation factor is ≈ 0.42, so that the vertical ground motion at the range of the vacuum equipment is 1.5×10^{-8} m at 30 Hz.




MATCHLINE FOR CONTINUATION SEE WA-H-113
MATCHLI
36"Ø
30"Ø
28"Ø
36"Ø
36"Ø
14"Ø
LARGE ITEM ACCESS AIRLOCK
106
24X18 RR 800 CFM
42"Ø
24X18 TR
@ 12" ABV FIN FLR
800 CFM
VEST 7
114
MECHANICAL ROOM
107
16"Ø
FD
FD
FD
36"Ø
36"Ø
14"Ø
30"Ø
42"Ø
24"Ø
LASER VACUUM EQUIPMENT AREA 4
104
36"Ø
42"Ø
30"Ø
14"Ø (TYP)
42"Ø
VEST 5
112
W-CS-107-HC-05
W-CS-107-HC-01
W-CS-107-HC-04
W-CS-107-HC-02
W-CS-107-HC-03
W-CS-107-HC-06
W-CS-107-SF-1A
W-CS-107-SF-1B
W-CS-107-SF-2A
W-CS-107-SF-2B
W-CS-107-CC-1A
W-CS-107-CC-1B
W-CS-107-AC-1A
W-CS-107-AC-1B
W-CS-107-CC-2A
W-CS-107-CC-2B
W-CS-107-HE-2B
W-CS-107-HE-2A
W-CS-107-HE-1B
W-CS-107-HE-1A
W-CS-107-AF-02
W-CS-107-HC-08
W-CS-107-AF-01
W-CS-107-HC-07
W-CS-107-AS-01
W-CS-107-TK-01
W-CS-107-GP-01
GLYCOL TANK
MAKEUP WATER TANK
60X24 OA INTAKE LOUVER
W-CS-107-CC-3B
W-CS-107-CC-3A
W-CS-107-HE-3A
W-CS-107-HE-3B
W-CS-107-HC-09
W-CS-107-HC-10
HF-1, 525 CFM (TYP FOR 16)
W-CS-107-SF-3A
W-CS-107-SF-3B
W-CS-107-AF-03
W-CS-107-HC-11
W-CS-107-HC-12
60X24 OA INTAKE LOUVER
CONTROL PANEL



(FILE: HV01.SDN)

INTEROFFICE CORRESPONDENCE

To: Tim Melott **Date :** Aug., 05, 1995

From: Atia Y. Atia **Ext.:** 4573 **Location:** WHQ-T669

Subject: Rotating Equipment Data

Chiller yard at the corner station:

Eq. No.	Eq. Name	Rotating Part	Qty	Weight	RPM	Unit Wt.	
CH-1	Chiller	Compressor	2	58	3600	6700	Rot
		Condenser Fan	10	12	850	24	Rot
CH-2	Chiller	Compressor	2	58	3600	6700	Rot
		Condenser Fan	10	12	850	24	Rot
CH-3	Chiller(Standby)	Compressor	2	58	3600	6700	Rot
		Condenser Fan	10	12	850	24	Rot
P-1	Pump	Impeller/Motor	1	210	3600	420	Rot
P-2	Pump	Impeller/Motor	1	210	3600	420	Rot
P-3	Pump(Standby)	Impeller/Motor	1	210	3600	420	Rot
EF-1	Exh. Fan	Impeller/Motor	1	29	1750	85	Rot
AC-1	Air Comp.	Compressor	1	90	3010 ~~1750~~	800 ~~650~~	Rot.

on roof of AHU

Corner Station (Main Mechanical Room):

AHU-1	Air Handler	Fan	2	750	1750	1150	Rot
AHU-2	Air Handler	Fan	2	750	1750	1150	Rot
AHU-3	Air Handler	Fan	2	550	1750	850	Rot

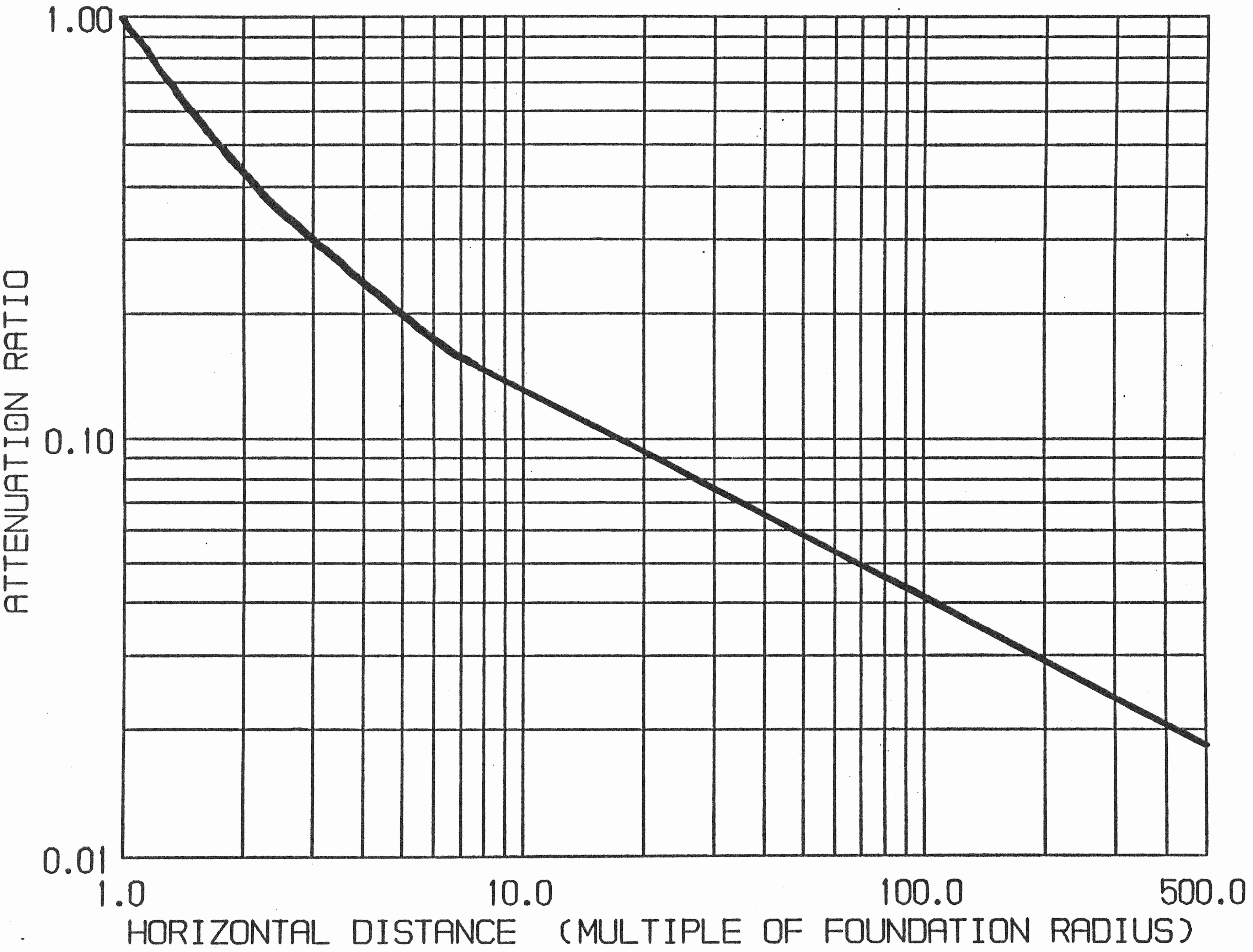
Corner Station (Small Mechanical Room):

AHU-4	Air Handler	Fan	1	220	1750	950	

Chiller yard at Mid or End Stations:

Eq. No.	Eq. Name	Rotating Part	Qty	Weight	RPM		
CH-1	Chiller	Compressor	2	120	3450	595	Rec.
		Condenser Fan	2	8	1100	16	Rot
CH-2	Chiller(Standby)	Compressor	2	120	3450	595	Rec.
		Condenser Fan	2	8	1100	16	Rot
P-1	Pump	Impeller/Motor	1	42	1750	95	Rot
P-2	Pump(Standby)	Impeller/Motor	1	42	1750	95	Rot
AHU-X	Air Handler	Fan	1	550	1750	850	Rot.

ATTENUATTION OF VERTICAL GROUND MOTIONS



PARSONS

Calculation Sheet

Job Number	Cost Center	Page Number	Sheet of
402117 21013	61-7123	1	

Rev	Date	By	Ck	Title Mid + End Station - HVAC Analysis

The soil properties are:

$G_s = 17{,}937$ psi

$\nu_s = 0.37$

$\gamma_s = 105\ lb/ft^3$

The plan area of the HVAC fan room at the Mid and End stations is

$A = 45{,}117\ in^2$

From Richart, Hall, and Woods, the vertical soil stiffness is

$$K_V = \frac{G_s}{1-\nu}\beta_z\sqrt{A}\ ,\quad \beta_z = 2.3$$

$$K_V = \left(\frac{17{,}937}{1-0.37}\right)(2.3)\sqrt{45{,}117} = 13{,}909{,}362\ lb/in$$

and the horizontal soil stiffness is

$$K_H = 2(1+\nu)\,G_s\,\beta_x\sqrt{A}\ ,\quad \beta_x = 0.96$$

$$K_H = 2(1.37)(17{,}937)(0.96)\sqrt{45{,}117} = 10{,}021{,}707\ lb/in$$

PARSONS Calculation Sheet	Job Number	Cost Center	Page Number	Sheet of
	402117 21013	01-7123	2	

Rev	Date	By	Ck	Title Mid + End Station – HVAC Analysis

There are 181 soil nodes in the finite element model, the equivalent area of the soil beam is,

$$A_{SB} = \frac{45,117}{181} = 249.265 \text{ in}^2$$

The arbitrary length of the soil beam is 24", and the total soil stiffness is known. Therefore the Young's Modulus of the soil beam can be determined.

$$E_{SB} = \frac{(K_v/181)(l)}{(A/181)} = \frac{(13,909,362)(24)}{(45,117)} = 7,399 \text{ psi}$$

The soil beams are fixed at their base and at the end connected to the nodes of the concrete foundation elements was pin connected, so lateral stiffness of the soil beam is,

$$K_{SBH} = \frac{3\ E_{SB}\ I_{SB}}{l_{SB}^3} = 10,021,707/181$$

Solving for the area moment of inertia of the soil beam, I_{SB} is;

$$I_{SB} = \frac{(10,021,707)(24)^3}{(181)(3)(7,399)} = 34,482 \text{ in}^4$$

PARSONS Calculation Sheet	Job Number	Cost Center	Page Number	Sheet of
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Rev	Date	By	Ck	Title Mid + End Station – HVAC Analysis

The area of the HVAC fan foundation is

$$A = 45{,}117 \text{ in}^2$$

The equivalent r_o for this area is

$$\pi r_o^2 = 45{,}117$$

$$r_o = \sqrt{\frac{45{,}117}{\pi}} = 119.84 \text{ in}$$

The weight of the concrete HVAC housing is

Floor (24" Thick), $W_F = \left(\frac{24 \times 45{,}117 \times 154}{1728}\right) = 96{,}500 \text{ lb}$

Roof (8" thick), $W_R = \left(\frac{8 \times 45{,}117 \times 154}{1728}\right) = 32{,}167 \text{ lb}$

Walls (8" Thick), $W_W = \left(\frac{8 \times 146{,}880 \times 154}{1728}\right) = 104{,}720 \text{ lb}$

$$W_{Total} = 233{,}387 \text{ lb}$$

From Richart, Hall, + Woods, Page 382

Vertical Damping

$$B_Z = \frac{(1-\nu)(m)}{4 \rho_o r_o^3} = \frac{(1-0.37)(233{,}387/g)}{(4)\left(\frac{105}{1728 \times g}\right)(119.84)^3} = 0.35148$$

$$D_Z = \frac{0.425}{\sqrt{B_Z}} = \frac{0.425}{\sqrt{0.35148}} = 0.717$$

Horizontal Damping

$$B_H = \frac{(7-8\nu)(m)}{32(1-\nu)\rho_o r_o^3} = \frac{(7-8 \times 0.37)(233{,}387/g)}{32(1-0.37)\left(\frac{105}{1728 \times g}\right)(119.84)^3} = 0.44721$$

$$D_H = \frac{0.288}{\sqrt{B_H}} = \frac{0.288}{\sqrt{0.44721}} = 0.4307$$

Use 43% of Critical Damping

PARSONS Calculation Sheet	Job Number	Cost Center	Page Number	Sheet of
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Rev	Date	By	Ck

Title Mid & End Station – HVAC Analysis

<u>Air Handler</u> AHU-X (1800 Rpm, 30 Hz)

W_R = (Rotor Weight) = 550 lb

W_T = (Total Weight) = 850 lb

Isolation Frequency = 5 Hz (Vertical & Horizontal)

$f = 5\,Hz = \frac{1}{2\pi}\sqrt{\frac{Kg}{W}}$; $K = \frac{AE}{l}$, vertical

$l = 48"$, distance from support to Cg

Let E = 1000 psi, the compute the area of the equivalent beam supporting fan. $g = 386.4\ in/s^2$

$$\frac{(10\pi)^2(48)(850)}{(1000)(386.4)} = A_{fb} = 104.21\ in^2$$

For the cantilever frequency equal to 5 Hz

$f = 5\,Hz = \frac{1}{2\pi}\sqrt{\frac{Kg}{W}}$, $K = \frac{3EI}{l^3}$, horizontal

Solving for I

$$I = \frac{(10\pi)^2(850)(48)^3}{(3)(1000)(386.4)} = 80{,}036\ in^4$$

Note the unbalanced vibrating force is

$F_{uf} = (0.1g)(550\ lb) = 55\ lb$

PARSONS **Calculation Sheet**	Job Number 402117 21013	Cost Center 01-7123	Page Number	Sheet of

Rev	Date	By	Ck	Title Mid + End Station - HVAC Analysis

Summary of finite element data.

Nodes

Nodes	1-181	Foundation nodes
Nodes	182-244	Wall nodes
Nodes	245-425	Roof nodes
Nodes	426-427	Fan motor nodes
Nodes	428-608	Soil nodes

Elements

Plate Element	1-152	Floor
Plate Elements	153-280	Wall
Plate Elements	281-432	Roof
Beam Elements	433-434	Motors
Beam Elements	435-615	Soil Beams

PARSONS Calculation Sheet	Job Number 402117 21013	Cost Center 01-7123	Page Number	Sheet of

Rev	Date	By	Ck	Title Mid + End Station - HVAC Analysis

Based on the final analyses of the HVAC concrete fan building at the Mid + End Stations the following displacements at the foundation of the fan building were computed. Note that these values were corrected from the values presented at the PDR. The large soil damping values had been inadvertently applied to the equipment isolation modes instead of the rigid body modes of the building.

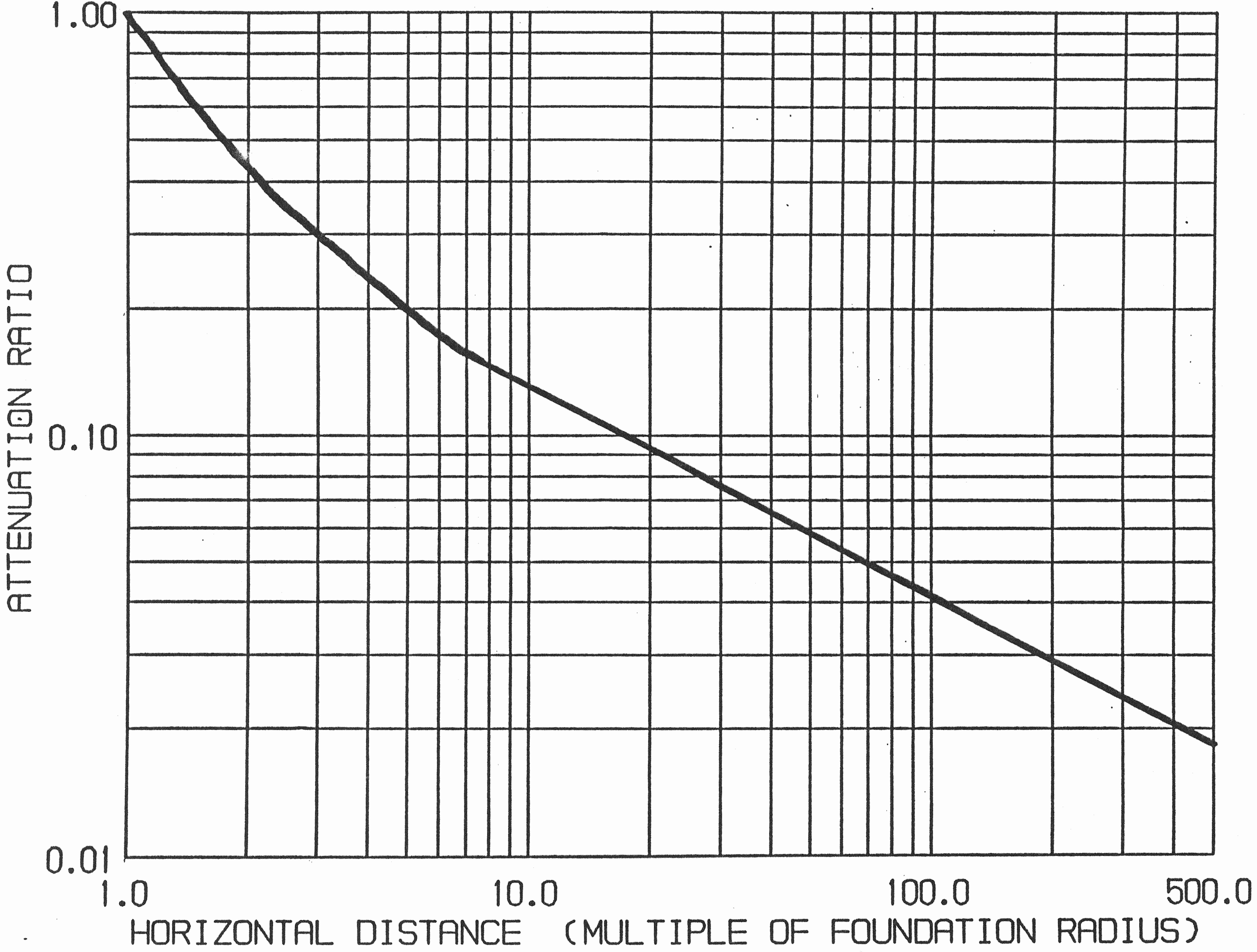
X direction (Horizontal) (Transverse) $= 0.8932 \times 10^{-7}$ in $= 2.27 \times 10^{-9}$ m

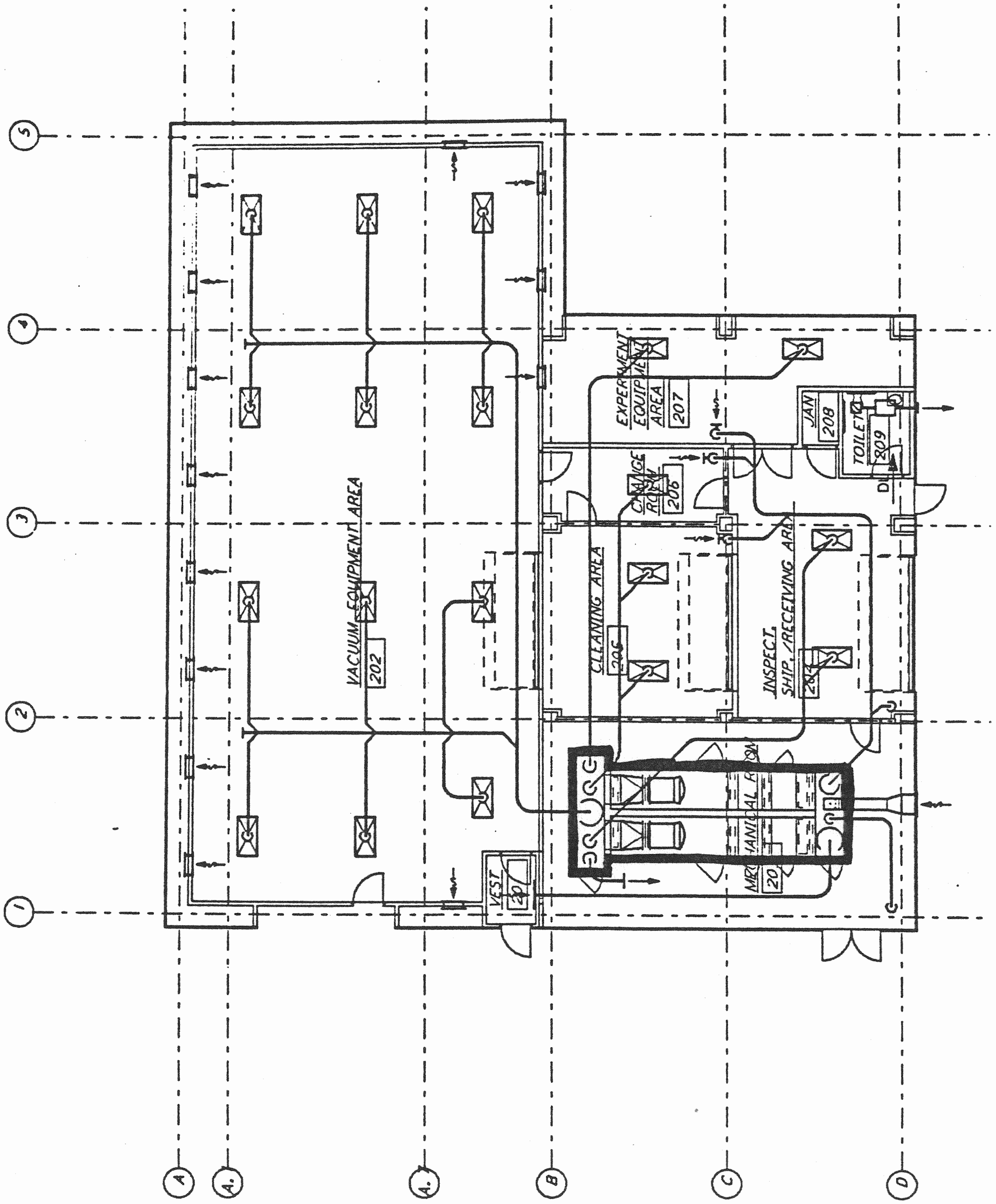
Y direction (Horizontal) (Longitudinal) $= 0.5010 \times 10^{-7}$ in $= 1.27 \times 10^{-9}$ m

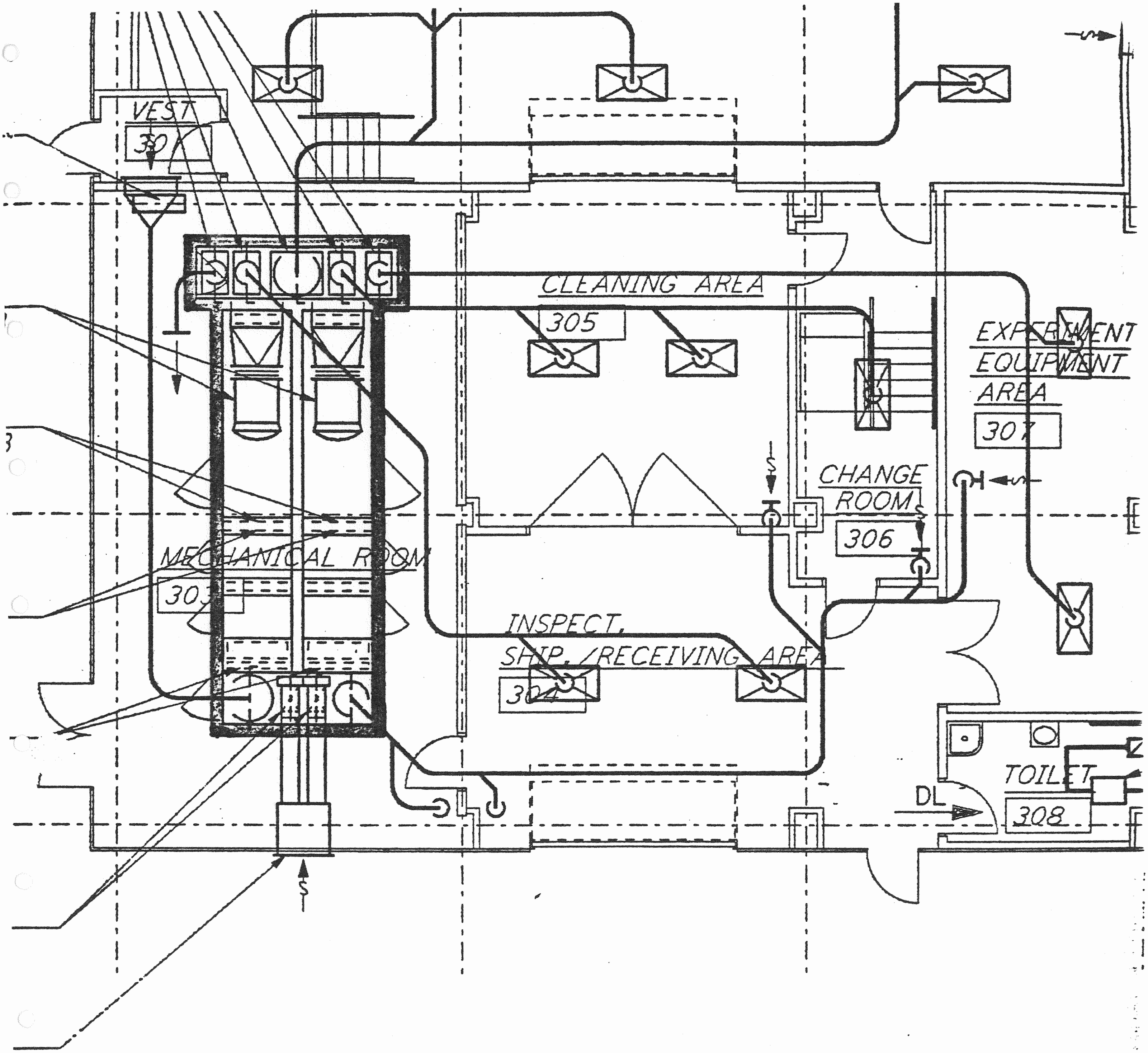
Z direction (Vertical) $= 0.54477 \times 10^{-6}$ in $= 13.84 \times 10^{-9}$ m

Note $r_0 = 119.84$ in ≈ 10 ft, and it is about 30 ft to the critical vacuum equipment. Thus $\frac{R}{r_0} = \frac{30}{10} = 3$, and the attenuation factor is ≈ 0.3, so that the vertical ground motion at the range of the vacuum equipment is 0.42×10^{-8} m @ 30 Hz

ATTENUATTION OF VERTICAL GROUND MOTIONS

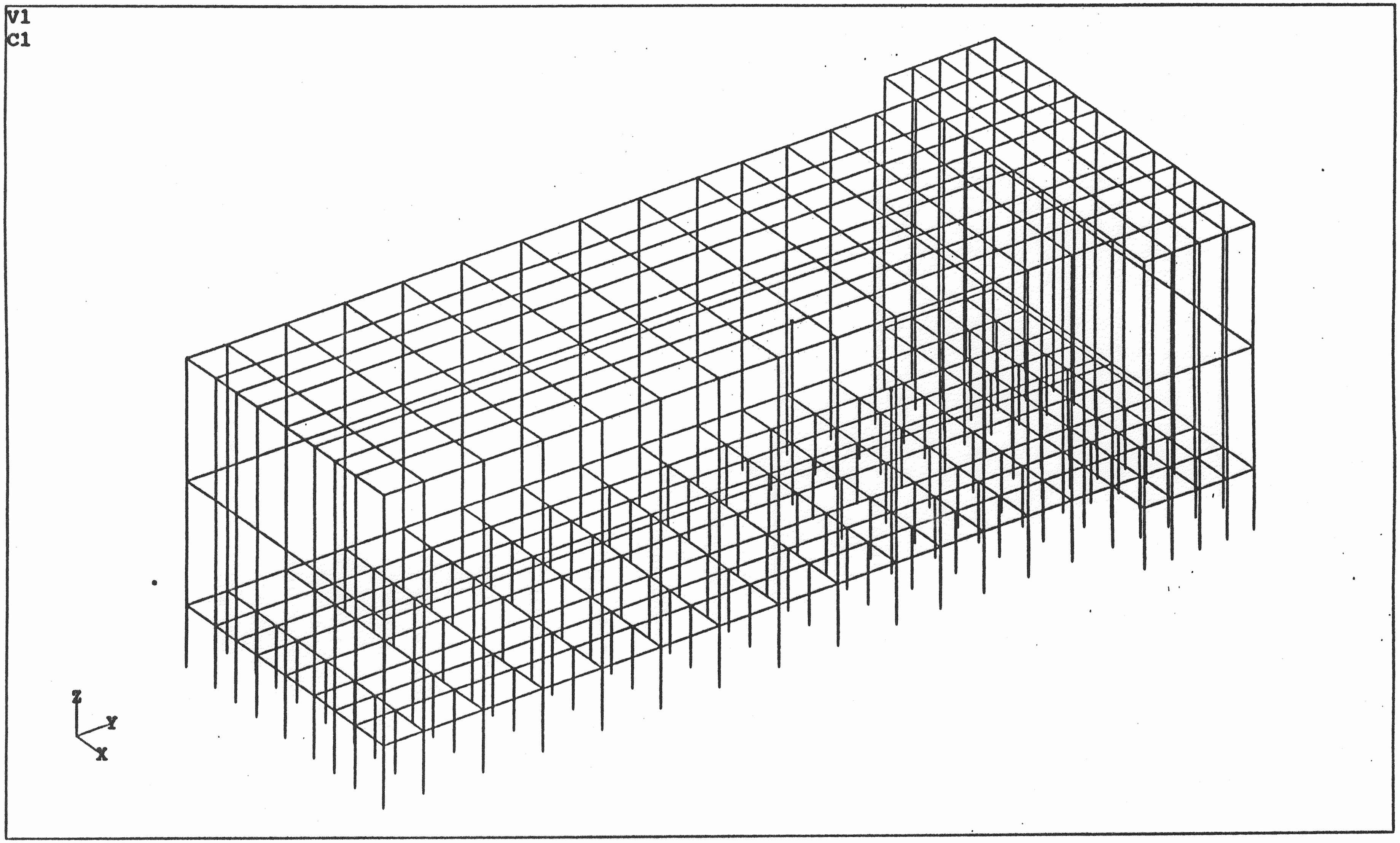



5
4
3
2
1
A
A.
A.
B
C
D
VACUUM EQUIPMENT AREA
202
CLEANING AREA
205
CHANGE ROOM
206
EXPERIMENT EQUIPMENT AREA
207
JAN
208
TOILET
209
INSPECT. SHIP./RECEIVING AREA
204
MECHANICAL ROOM
20
VEST
201
DL



END STATION "B" FLOOR PLAN

$\frac{1}{8}$" =1'-0"



(FILE: HVM01.SDN)

INTEROFFICE CORRESPONDENCE

To: Tim Melott **Date :** Aug., 05, 1995

From: Atia Y. Atia **Ext.:** 4573 **Location:** WHQ-T669

Subject: Rotating Equipment Data

Chiller yard at the corner station:

Eq. No.	Eq. Name	Rotating Part	Qty	Weight	RPM	Unit Wt.	
CH-1	Chiller	Compressor	2	58	3600	6700	Rot
		Condenser Fan	10	12	850	24	Rot
CH-2	Chiller	Compressor	2	58	3600	6700	Rot
		Condenser Fan	10	12	850	24	Rot
CH-3	Chiller(Standby)	Compressor	2	58	3600	6700	Rot
		Condenser Fan	10	12	850	24	Rot
P-1	Pump	Impeller/Motor	1	210	3600	420	Rot
P-2	Pump	Impeller/Motor	1	210	3600	420	Rot
P-3	Pump(Standby)	Impeller/Motor	1	210	3600	420	Rot
EF-1	Exh. Fan	Impeller/Motor	1	29	1750	85	Rot
AC-1	Air Comp.	Compressor	1	90	3010 ~~1750~~	800 ~~650~~	Rot.

on roof of AHU

Corner Station (Main Mechanical Room):

AHU-1	Air Handler	Fan	2	750	1750	1150	Rot
AHU-2	Air Handler	Fan	2	750	1750	1150	Rot
AHU-3	Air Handler	Fan	2	550	1750	850	Rot

Corner Station (Small Mechanical Room):

AHU-4	Air Handler	Fan	1	220	1750	950

Chiller yard at Mid or End Stations:

Eq. No.	Eq. Name	Rotating Part	Qty	Weight	RPM		
CH-1	Chiller	Compressor	2	120	3450	595	Rec.
		Condenser Fan	2	8	1100	16	Rot
CH-2	Chiller(Standby)	Compressor	2	120	3450	595	Rec.
		Condenser Fan	2	8	1100	16	Rot
P-1	Pump	Impeller/Motor	1	42	1750	95	Rot
P-2	Pump(Standby)	Impeller/Motor	1	42	1750	95	Rot
AHU-X	Air Handler	Fan	1	550	1750	850	Rot.

9. Chiller Equipment Vibrations

The Chiller equipment vibration predictions are based on either mounting the Chiller equipment directly on the concrete foundation or using a 5 Hz isolation system to support the Chiller equipment skids. The analyses are based on the rotating equipment (two screw type compressors) operating at 3600 rpm (60 Hz). An unbalanced force equal to 0.1g times the rotor weight is used to provide an upper bound to the unbalanced vibrations. It is expected that the acceptance level of unbalanced force will be approximately 1/4 of this extreme force. The reason for using this conservative estimate of the forcing function is to allow for normal wear so that excessive maintenance on the rotating equipment would not be required. It is expected that an annual inspection in conjunction with appropriate maintenance would be sufficient to keep the rotating equipment operating within this vibration range. The Chiller yards are located approximately 300 feet from the technical foundations at the corner station, mid station, and end station. A hand calculation was made to estimate the Chiller equipment foundation vibration amplitude based on the unbalanced forces and the 5 Hz isolation system. The foundation motions were reduced by estimating the attenuation of the ground surface vibrations emanating from the Chiller yard and traveling the 300 feet to the technical foundation. The resultant ground motion at the technical foundation location is $2.9X10^{-9}$ m at 60 Hz based on a hard mounted Chiller system having no isolation. The spike amplitude criteria limits the peak amplitude to $3.0X10^{-9}$ m at 60 Hz. If a 5 Hz isolation system is used the ground motions expected at the LVEA might be reduced to $2.3X10^{-11}$ m. at 60 Hz. Note that at isolation frequency ratios above ten, for example for the operating frequency at 60 Hz divided by the isolation frequency of 5 Hz, there is a possibility of surge vibrations in the isolators that will significantly reduce the effectiveness of the isolation system. The effect of isolator surges could result in ground motions at the LVEA ten times greater than predicted, or about $3.0X10^{-10}$ m. These amplitude estimates did not include the reductions associated with moving the relatively rigid and massive concrete technical foundations on top of the ground which could reduce the vibrations by a multiplication factor of 1/4 or 1/5. It is evident that the new Chiller systems implemented after the conceptual design was completed have significantly reduced the vibrations produced by the 60 Hz compressors.

PARSONS

Calculation Sheet

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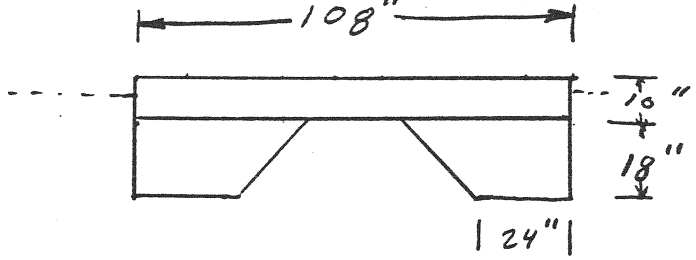
Title Chiller Vibrations

The water chiller pad is 9'-0" by 18'-6" in plan area. The pad is 10 inches thick with a perimeter beam 18" below the 10" pad and 24" wide at the base.



The equivalent thick slab is 22.5" thick

The area of the slab is 23,976 in^2

The equivalent radius is $r = \sqrt{\frac{A}{\pi}} = 87.36 in = 7.28'$

Compressors

There are two compressors (screw type) operating at 3600 rpm (60 Hz) with a rotor weight of 58 lb each.

The vibrating force, assuming both in phase, is equal to 0.1g × 58 lb × 2 = 11.6 lb

The total weight of the chiller equipment is 6700 lb and will be supported on 5 Hz isolators. Therefore the acceleration of the chiller will be: F = ma

$$\ddot{x}_c = \frac{11.6\,lb}{6700\,lb/g} = 1.73 \times 10^{-3}\, g \quad @ \; 60 Hz$$

ENG-GE-30 (050492)

PARSONS

Calculation Sheet

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Rev	Date	By	Ck

Title Chiller Vibrations

The transmissibility of this force to the chiller pad is, Ref. Page 77, Thomson, W.T. Mechanical Vibrations

$$T_r = \frac{1}{\left(\frac{\omega}{\omega_n}\right)^2 - 1}$$

$$T_r = \frac{1}{\left(\frac{60}{5}\right)^2 - 1} = 6.993 \times 10^{-3}$$

For a 60 Hz excitation force on a 5 Hz isolation system.

Thus the 11.6 lb force applied to the chiller mass will result in the following force being applied to the chiller foundation

$$F_{TR}/F_0 = 6.993 \times 10^{-3} = T_r$$

$$F_0 = 11.6 \text{ lb}$$

$$F_{TR} = 11.6 \times 6.993 \times 10^{-3} = 8.112 \times 10^{-2} \text{ lb}$$

The foundation mass is

$$M_f = \frac{\left(9 \times 18.5 \times \frac{22.5}{12}\right)(150 \text{ lb/ft}^3)}{g} = \frac{46,828 \text{ lb}}{g}$$

ENG-GE-30 (050492)

PARSONS Calculation Sheet	Job Number 402117 21013	Cost Center 01-7123	Page Number 3	Sheet of

Rev	Date	By	Ck	Title Chiller Vibrations

Thus the acceleration of the chiller foundation becomes;

$$\ddot{x}_{cf} = \frac{F_{TR}}{m_f} = \frac{8.112\times10^{-2}\,lb}{46,828\,lb/g} = 1.73\times10^{-6}\,g$$

The attenuation that is achieved based on the propagation of the chiller foundation vibrations over the 300 ft to the LVEA or VEA foundations can be calculated from the attached figure.

Based on the horizontal distance ratio

$$\mathcal{R}_h = \frac{300\,ft}{7.28\,ft} = 41.2$$

where 7.28 ft is the equivalent radius of the chiller foundation

From this figure the attenuation ratio is equal to 0.065

Thus the ground acceleration at the LVEA is

$$\ddot{x}_{cfL} = (1.73\times10^{-6}\,g)(0.065) = 1.125\times10^{-7}\,g \text{ @60Hz}$$

This is equivalent to a displacement of

$$\omega^2 x_{cfL} = \ddot{x}_{cfL}$$

$$x_{cfL} = \frac{\ddot{x}_{cfL}}{\omega^2} = \frac{(1.125\times10^{-7}\,g)(9.8\,m/sec^2/g)}{(2\pi 60)^2} = 7.75\times10^{-12}\,m$$

PARSONS Calculation Sheet	Job Number	Cost Center	Page Number	Sheet of
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Rev	Date	By	Ck	Title Chiller Vibrations

The spike amplitude criteria limits the peak amplitude to 3.0×10^{-9} m at 60 Hz. Note that there are three chiller systems operating simultaneously so the combined vibrations could be as much as 2.33×10^{-11} m @ 60 Hz, at the technical foundations. Note that AcenTech commented that surge frequencies in the isolation systems can significanty reduce the reductions predicted by the ideal transmissibility factor. This is especially important for large frequency ratios, that is when f/f_n, 60/5 becomes larger the ten.

Another approach to estimating the chiller foundation vibration is to assume the "worst case" when the chiller is hard mounted on the chiller pad. In this case the chiller and pad mass can be combined so that the chiller foundation acceleration is

$$\ddot{x}_{cf*} = \frac{11.6\,lb}{\{6700\,lb + 46{,}828\,lb\}/g} = 2.167 \times 10^{-4}\,g$$

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The attenuation based on range, 300 ft, is 0.065 as before, so the ground motion at the LVEA becomes

$$\ddot{x}_{cf*L} = (2.167\times10^{-4})(0.065) = 1.409\times10^{-5}\,g$$

This is equivalent to a displacement of:

$$x_{cf*L} = \frac{\ddot{x}_{cf*L}}{\omega^2} = \frac{(1.409\times10^{-5})(9.8\,m/sec^2/g)}{(2\pi 60)^2} = 9.71\times10^{-10}\,m$$

Since there a three chillers operating simultaneously the ground motion at the LVEA could be equal to 2.9×10^{-9} m. Note that this is essentially equal to the spike amplitude criteria of 3×10^{-9} m at 60 Hz.

PARSONS Calculation Sheet	Job Number 402117 21013	Cost Center 01-7123	Page Number 6	Sheet of

Rev	Date	By	Ck	Title Chiller Vibrations

Condenser fans

There are ten condenser fans with 12 lb rotor weights, each. The condenser fans rotate at 850 rpm, 14 Hz. Using the nominal unbalanced force of 0.1g, the total unbalanced force becomes:

$$F_o = (0.1g)(12\,lb)(10) = 12\,lb$$

If the chillers are isolated, the transmissibility is, $T_r = \frac{1}{\left(\frac{14.17}{5}\right)^2 - 1} = 1.423 \times 10^{-1}$

$$F_{Tr} = F_o T_r = 12 \times 0.1423 = 1.7075\ lb$$

The foundation mass is 46,828 lb/g and the acceleration of the chiller foundation becomes

$$\ddot{x}_{cf} = \frac{F_{TR}}{m_f} = \frac{1.7075\ lb}{46{,}828\ lb/g} = 3.646 \times 10^{-5}\ g \text{ at } 14Hz$$

The ground acceleration at the LVEA becomes

$$\ddot{x}_{CfL} = (3.646 \times 10^{-5} g)(0.065) = 2.370 \times 10^{-6}\ g$$

Or the displacement is

$$x_{CfL} = \frac{\ddot{x}_{CfL}}{\omega^2} = \frac{(2.370 \times 10^{-6})(9.8\ m/sec^2/g)}{(2\pi\ 14.17)^2} = 2.93 \times 10^{-9}\ m$$

Since three chillers can operate simultaneously the displacement could be 8.79×10^{-9} m

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If the chiller is hard mounted to the chiller foundation, then the foundation acceleration is

$$\ddot{x}_{cf*} = \frac{12\ lb}{(6{,}700+46{,}828)\ lb/g} = 2.2418\times10^{-4}\ g$$

Based on the attenuation due to transmitting the vibrations 300 ft to the LVEA, the ground motion at the LVEA is.

$$\ddot{x}_{cf*L} = (2.2418\times10^{-4})(0.065) = 1.457\times10^{-5}\ g$$

This equivalent to a displacement of

$$x_{cf*L} = \frac{\ddot{x}_{cf*L}}{\omega^2} = \frac{(1.457\times10^{-5}\ g)(9.8\ m/sec^2/g)}{(2\pi\ 14.17)^2} = 18.02\times10^{-9}\ m$$

or 54.1×10^{-9} m with three chillers operating simultaneously.

Note, since the spike amplitude criteria limit for the frequency range of 1 Hz to 50 Hz is $5.0\times10^{-4}\ m/sec^2$

For the hard mounted chiller system the acceleration at the LVEA with three chillers operating is $(1.457\times10^{-5})(3)(9.8\ m/sec^2/g)$ $\cong 4.3\times10^{-4}\ m/sec^2$ at 14 Hz. With a 5 Hz isolation system this becomes $(2.37\times10^{-6})(3)(9.8)$ $= 0.7\times10^{-4}\ m/sec^2$.

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Pumps

The pumps used to drive the chilled water are located on idividual foundations; The foundations are 3.5 ft by 4.5 ft in plan and are 2.5 ft thick. The pump impeller weighs 210 lb, the pump weighs 420 lb, and operates at 3600 rpm (60 Hz).

The unbalanced force of the rotor is

$$F_o = (0.1g)(210\,lb) = 21\,lb$$

The transmissibility of the isolation system is

$$T_r = 6.993 \times 10^{-3}$$

60 Hz forcing frequency and 5 Hz isolation frequency

The force transmitted to the foundation is

$$F_{TR} = F_o T_r = (21\,lb)(6.993 \times 10^{-3}) = 0.14685\,lb$$

The foundation mass is

$$m_f = \frac{(3.5 \times 4.5 \times 2.5 \times 150\,lb/ft^3)}{g} = \frac{5906\,lb}{g}$$

Thus the acceleration of the pump foundation is

$$\ddot{x}_{pf} = \frac{F_{TR}}{m_f} = \frac{0.14685\,lb}{5906\,lb/g} = 2.4864 \times 10^{-5}\,g$$

The equivalent radius of the pump foundation is

$$r_o = \sqrt{\frac{3.5 \times 4.5}{\pi}} = 2.24\,ft$$

PARSONS

Calculation Sheet

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Based on the attenuation figure for range

$$R_1 = \frac{300\,ft}{2{,}239\,ft} = 134$$

The attenuation factor become 0.022, and the acceleration at the technical foundation becomes

$$\ddot{x}_{pfL} = (2.4864\times10^{-5} g)(0.022) = 5.47\times10^{-7} g$$

this is equivalent to a displacement of

$$x_{pfL} = \frac{\ddot{x}_{pfL}}{\omega^2} = \frac{5.47\times10^{-7} g}{(2\pi 60)^2} = 3.85\times10^{-12}\,m$$

For three chiller pumps operating this becomes $x_{pfL} = 1.15\times10^{-11}\,m$

<u>For hard mounted pumps</u>

$$F_o = 21\,lbf$$

The acceleration of the pump and foundation

$$\ddot{x}_{hf} = \frac{21\,lbf}{(420\,lbf + 5906\,lbf)/g} = 3.32\times10^{-3} g$$

The attenuation for range is 0.022

$$\ddot{x}_{hfL} = (3.32\times10^{-3})(0.022) = 7.30\times10^{-5} g$$

This is equivalent to a displacement of

$$x_{hfL} = \frac{7.30\times10^{-5} g}{(2\pi 60)^2} = 5.14\times10^{-10}\,m$$

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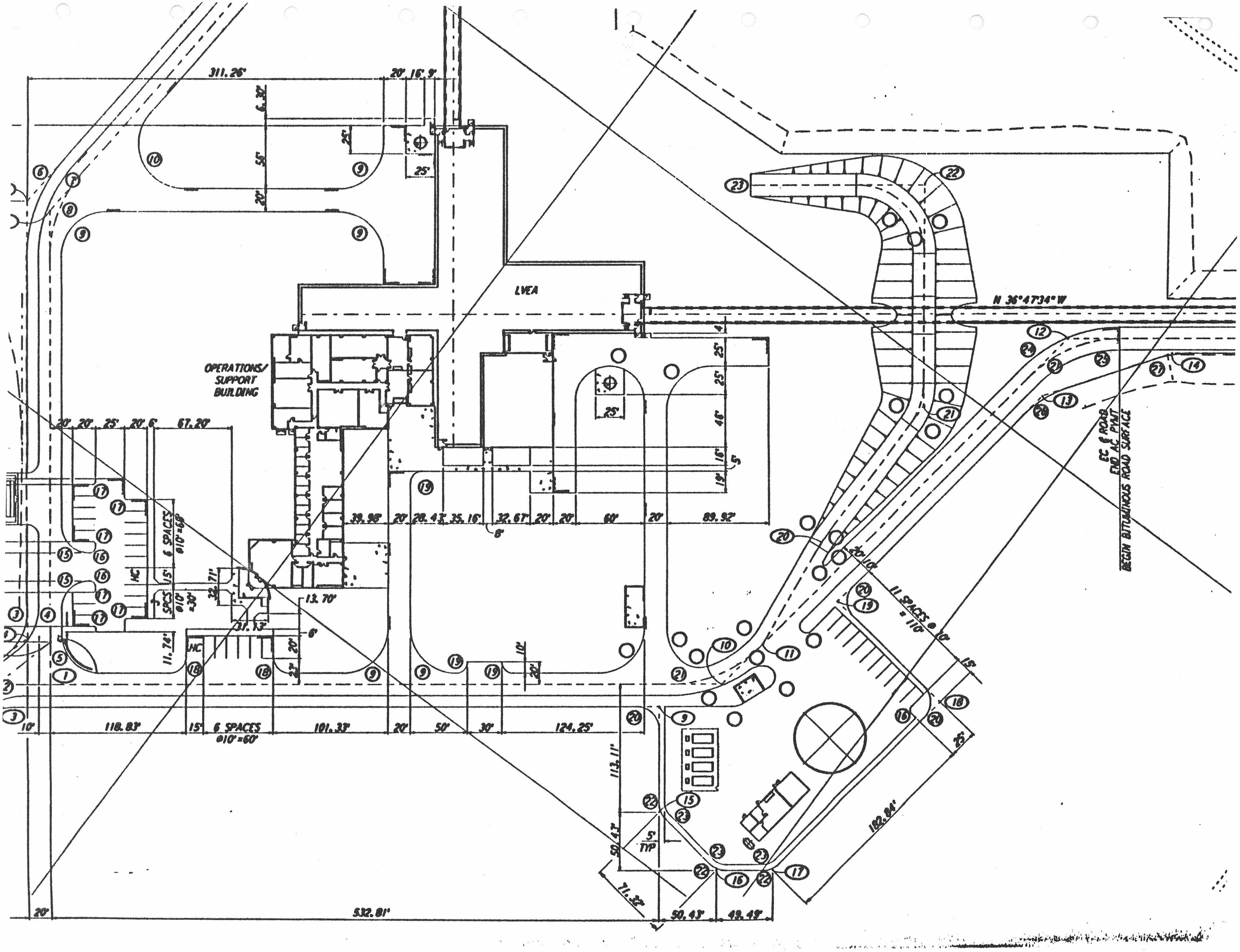
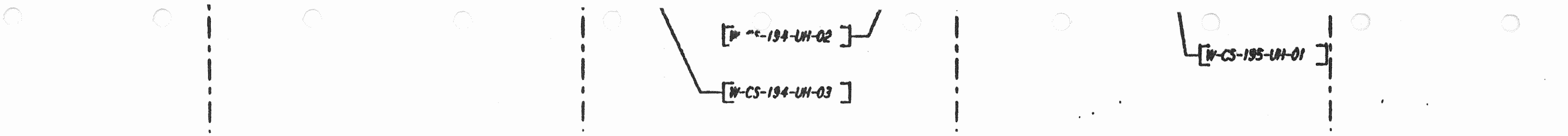
Thus for three chiller pumps operating the hard mounted pumps would produce

1.54×10^{-9} m @ 60 Hz

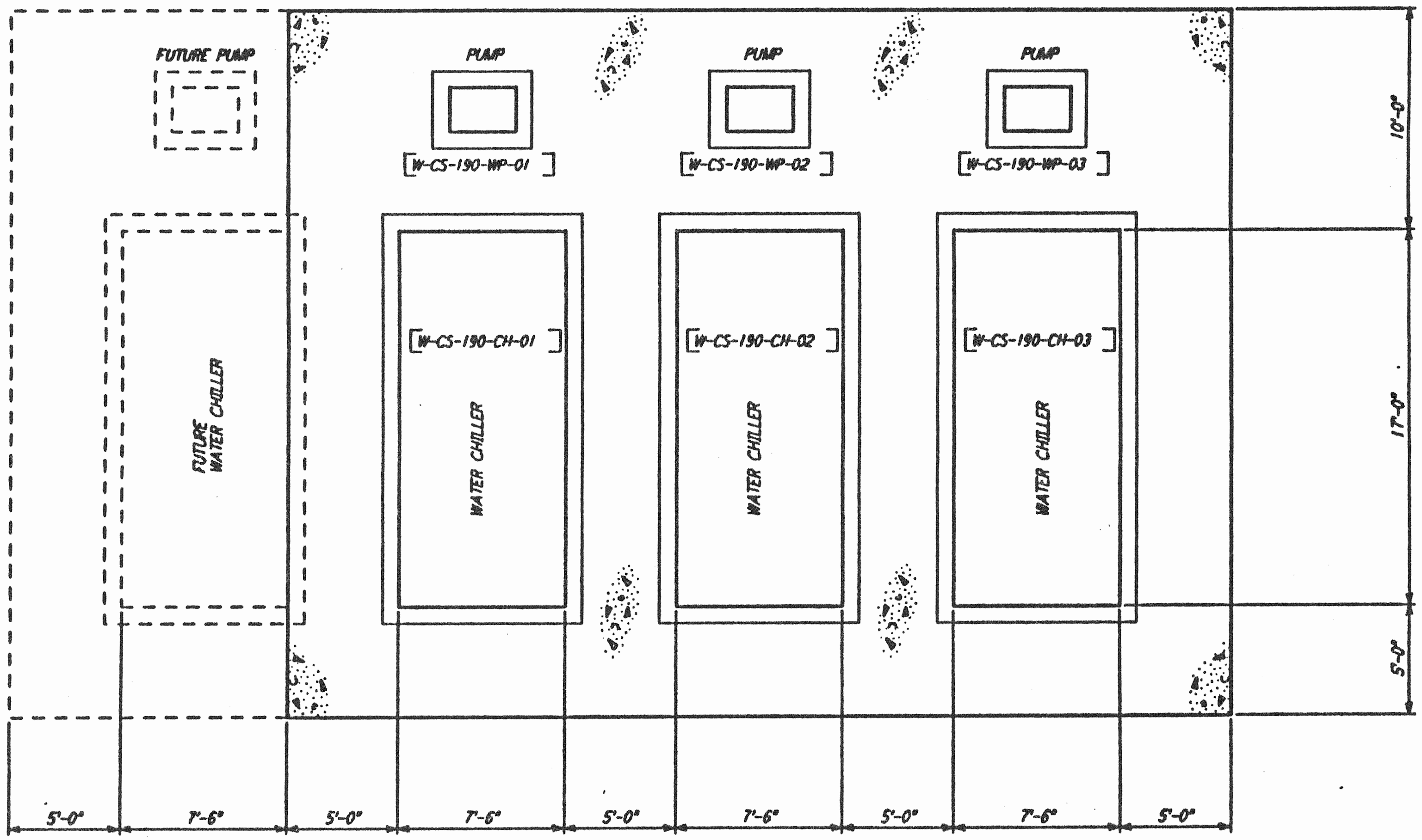
Since the spike amplitude permitted at 60 Hz is equal to 3.0×10^{-9} m and the hard mounted result is 1.54×10^{-9} m and the isolated pump produces 1.15×10^{-11} m of displacement it is not madatory that the pumps be isolated to satisfy the criteria. However, it is clear that an isolation system would significantly reduce the vibrations generated at the LVEA or VEA foundations.


OPERATIONS/ SUPPORT BUILDING
LVEA
N 36°47'34"W
EC & ROAD
END AC PVMT
BEGIN BITUMINOUS ROAD SURFACE
11 SPACES @ 10' = 110'
6 SPACES @10'=60'
6 SPACES @10'=60'
5 SPCS @10' =30'
HC
5' TYP
311.26'
20'
16.9'
6.30'
56'
25'
67.20'
39.98'
28.43'
35.16'
32.67'
60'
89.92'
4'
46'
16'
19'
5'
8'
13.70'
31.13'
32.71'
11.74'
118.83'
15'
101.33'
50'
30'
124.25'
10'
113.11'
50.43'
71.32'
49.49'
182.84'
532.81'



MAINTENANCE BUILDING FLOOR PLAN

¼" =1'-0"



CHILLER YARD PLAN

¼" =1'-0"

INTEROFFICE CORRESPONDENCE

To: Tim Melott **Date :** Aug., 05, 1995

From: Atia Y. Atia **Ext.:** 4573 **Location:** WHQ-T669

Subject: Rotating Equipment Data

Chiller yard at the corner station:

Eq. No.	Eq. Name	Rotating Part	Qty	Weight	RPM	Unit Wt.	
CH-1	Chiller	Compressor	2	58	3600	6700	Rot
		Condenser Fan	10	12	850	24	Rot
CH-2	Chiller	Compressor	2	58	3600	6700	Rot
		Condenser Fan	10	12	850	24	Rot
CH-3	Chiller(Standby)	Compressor	2	58	3600	6700	Rot
		Condenser Fan	10	12	850	24	Rot
P-1	Pump	Impeller/Motor	1	210	3600	420	Rot
P-2	Pump	Impeller/Motor	1	210	3600	420	Rot
P-3	Pump(Standby)	Impeller/Motor	1	210	3600	420	Rot
EF-1	Exh. Fan	Impeller/Motor	1	29	1750	85	Rot
AC-1	Air Comp.	Compressor	1	90	3010 ~~1750~~	800 ~~650~~	Rot.

on roof of AHU

Corner Station (Main Mechanical Room):

AHU-1	Air Handler	Fan	2	750	1750	1150	Rot
AHU-2	Air Handler	Fan	2	750	1750	1150	Rot
AHU-3	Air Handler	Fan	2	550	1750	850	Rot

Corner Station (Small Mechanical Room):

AHU-4	Air Handler	Fan	1	220	1750	950

Chiller yard at Mid or End Stations:

Eq. No.	Eq. Name	Rotating Part	Qty	Weight	RPM		
CH-1	Chiller	Compressor Condenser Fan	2 2	120 8	3450 1100	595 16	Rec. Rot
CH-2	Chiller(Standby)	Compressor Condenser Fan	2 2	120 8	3450 1100	595 16	Rec. Rot
P-1	Pump	Impeller/Motor	1	42	1750	95	Rot
P-2	Pump(Standby)	Impeller/Motor	1	42	1750	95	Rot
AHU-X	Air Handler	Fan	1	550	1750	850	Rot.

10. Foundation Thickness Trade Study

A foundation thickness trade study was made for the technical foundations that considered 68-inch thick foundations, 36-inch thick foundations, and 18-inch thick foundations. The results of the various analyses indicated that the acoustical response of the technical foundations appeared to be critical. The ambient PSD analyses indicated that the fundamental modes of the foundations would be heavily damped and not exceed two times the ambient PSD spectra with the criteria limit being four times the ambient PSD spectra. Note this result applied to all of the technical foundation thicknesses studied and for the LVEA and VEA foundation types. The spike amplitude responses at the technical foundations for wind induced vibrations, HVAC fan induced vibrations, and Chiller equipment induced vibrations were not evaluated in detail as to the effects of foundation thicknesses. However, it is not expected that there is an effect due to foundation thickness that is much more than the relative mass of the foundations. Thus the 36-inch thick foundation would have approximately twice the spike amplitude of the 68-inch thick foundation and the 18-inch thick foundation would have four times the spike amplitude of the 68-inch thick foundation. The deformation of the technical foundations based on changes in air temperature indicated that there were some small benefits to a thicker foundation. However, based on the 50 nano-radian curvature over a two meter long foundation length for a ten minute time interval, the region of unacceptable curvature was not significantly different for the various foundation thicknesses. Therefore the most significant analysis results were for the acoustically induced vibrations that showed the 18-inch thick technical foundations were not acceptable, the 36-inch thick foundations satisfied the criteria and the 68-inch thick foundation provided a significant margin of safety. The 68-inch thick foundation thickness used as a baseline in these analyses remains as the preferred thickness based on technical considerations since it provides a significant margin of safety. The 36-inch thick foundation appears to meet the criteria but does not provide any margin of safety and given the inexact nature of the vibration calculations there could be significant differences between the predicted vibrations and the actual vibrations measured at the completed facility. Note that the 36-inch thick foundation thickness is being considered for cost reduction reasons for the LVEA, the 68-inch technical foundation thickness for the VEA foundations at the Mid Station and End Station should not be reduced since it is evident that there would not be significant cost savings for these small foundations. The Mid Stations and End Stations have higher spike amplitude vibrations than the LVEA foundation and would benefit from a thicker foundation. Also the End Station technical foundation must withstand the thrust forces produced by the vacuum pressures and a thicker foundation would be beneficial.

11. Conclusions

The result of the vibration analyses completed to date indicate that the foundation responses to ambient ground motion PSD inputs do not exceed the broadband spectra requirements.

The technical foundation responses to acoustical noise cause the 18-inch thick technical foundations to exceed the broadband spectra requirements.

The thermally induced distortions may exceed the fifty nano-radian deformation limit over a two meter foundation length in a ten minute time period. The extreme deformations occur around the perimeter of the foundation. Also these thermally induced deformations are produced when the external building heat loads are rapidly changing. At other times of day the air temperature changes will be considerably less.

The wind induced vibration predictions remain to be accurately estimated. At this time, the best information available are the Moses Lake measurements that indicate the broadband foundation vibration levels are not significantly increased above the ambient vibrations for wind speeds up to 20 mph. Further literature research and study should be directed at verifying this conclusion.

The isolated HVAC fans and concrete fan room support building reduce the spike amplitudes of the 1800 rpm (30 Hz) fans transmitted to the technical foundations to levels that are below the spike amplitude criteria limits.

The Chiller equipment located 300 feet from the technical foundation also produces spike amplitudes at the technical foundations that are below the spike amplitude criteria.

Appendix A

Computer Results For Ambient PSD Induced Vibrations

Book 1

- LVEA Model T = 68 Inches
- LVEA Model T = 36 Inches

Book 2

- LVEA Model T = 18 Inches
- LVEA PSD Plots
    - Correlated -- COR
    - Uncorrelated -- UNC

Book 3

- MID-PB1 Model T = 68 Inches
- MID-PB1 Model T = 36 Inches
- MID-PB1 Model T = 18 Inches
- Mid Station PSD Plots
    - Correlated -- COR
    - Uncorrelated -- UNC
- END-PB1 Model T = 68 Inches
- END -PB1 Model T = 36 Inches
- END -PB1 Model T = 18 Inches
- End Station PSD Plots
    - Correlated -- COR
    - Uncorrelated -- UNC

Appendix B

Computer Results For Acoustically Induced Vibrations

Section 1

- 68 Inch LVEA -- LIGO Acoustic Criteria
- 68 Inch LVEA -- Marshall Long's SPL
- 36 Inch LVEA -- LIGO Acoustic Criteria
- 36 Inch LVEA -- Marshall Long's SPL
- 18 Inch LVEA -- LIGO Acoustic Criteria
- 18 Inch LVEA -- Marshall Long's SPL

Section 2

- 68 Inch Mid Station -- LIGO Acoustic Criteria
- 68 Inch Mid Station -- Marshall Long's SPL
- 36 Inch Mid Station -- LIGO Acoustic Criteria
- 36 Inch Mid Station -- Marshall Long's SPL
- 18 Inch Mid Station -- LIGO Acoustic Criteria
- 18 Inch Mid Station -- Marshall Long's SPL

Section 3

- 68 Inch LVEA -- LIGO Acoustic Criteria Uncorrelated

Appendix C

Computer Results For Thermally Induced Deformations

Book 1

- LIGO Heat Transfer Program
- 10 Minute Thermal Gradient -- 68 Inch Slab

Book 2

- 10 Minute Thermal Gradient -- 36 Inch Slab

Book 3

- 10 Minute Thermal Gradient -- 18 Inch Slab

Appendix D

Computer Results For HVAC Equipment Vibrations

- HVAC Vibration Model -- LVEA
- HVAC Vibration Model -- VEA