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Structural Analysis of the GEM Central Detector Support

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Abstract:

This report describes the structural analysis of the central detector support for the GEM detector. The concept is a segmented double membrane which supports the calorimeters and central tracker inside the solenoid magnet. The main issues to be addressed in this report are whether the central detector support can act independently from the magnet halves and whether longitudinal stiffening is needed in the form of gussets or spokes to stabilize the structure during operational and maintenance periods. Fabrication techniques, cost, schedule, central detector assembly procedures, and central detector alignment precision are not considered to be within the scope of this report.

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Introduction

This report describes the structural analysis of the central detector support for the GEM detector. The concept is a segmented double membrane which supports the calorimeters and central tracker inside the solenoid magnet. The main issues to be addressed in this report are whether the central detector support can act independently from the magnet halves and whether longitudinal stiffening is needed in the form of gussets or spokes to stabilize the structure during operational and maintenance periods. Fabrication techniques, cost, schedule, central detector assembly procedures, and central detector alignment precision are not considered to be within the scope of this report.

Structural Design Requirements

The structural design requirements may be classified into two broad categories: (1.) operational and (2.) maintenance modes. Within each category the structure will be evaluated from a static stress and deflection, elastic buckling, earthquake response spectrum, and ambient vibration stability. The difference between the operational mode and the maintenance mode is the amount and point of application of the dead load from the calorimeters. The operational mode assumes all calorimeters are in place and the center of gravity is directly over the center line of the membrane disks. The total calorimeter load is assumed to be 2200 Mg. The maintenance mode assumes one end cap calorimeter is removed so the center of gravity is shifted and the dead load from the calorimeter is reduced to 1600 Mg.

The load cases and failure criteria were developed because of the lack of established design requirements for unique structures (pertaining to detectors) and are considered to be much more conservative than codes applicable to civil structures. They were selected by the GEM muon subsystem engineer, calorimeter subsystem engineer, central tracker subsystem engineer, central detector support engineers, and the chief engineer. They are intended to provide a basis for selecting a conservative conceptual design for the central detector support and are not intended to be adopted as final criteria for the detailed design of the structure. They should evolve and become more refined as the detailed design progresses.

For both the operational mode and the maintenance mode the structure will have to support its static weight. The maximum allowable stress in the structure should be less than 50% of the material's yield strength. As a general guideline a standard structural steel such as A36 has a minimum yield strength of 36,000 psi and an ultimate strength of approximately 70,000 psi. No limits were set on the maximum allowable deflection of the structure.

From a global standpoint setting a criteria on the structure's resistance to buckling is much more subjective. The structure may have low buckling eigenvalues which exhibit localized characteristics that can be mitigated with minor modifications. To be consistent with the conservative design approach and given the uncertainty in the model, uncertainty in the calculation procedure, and uncertainty in post buckling behavior a minimum factor of safety of 5 on the buckling eigenvalue was selected as the criteria for both the operational and maintenance modes.

The seismic requirement chosen was the Comanche Peak Steam Generating plant safe shutdown response spectrum. Comanche Peak is a nuclear power plant in the Fort Worth area. A safe shutdown earthquake represents a severe earthquake for the region which a nuclear power plant must survive with no safety related systems damage (although non-safety related structural damage is acceptable). The DOE publishes design guidelines for its facilities with respect natural hazards, i.e. earthquakes, tornadoes, floods, etc. However, because of the young age of the SSCL these guidelines pertinent to the SSCL have not yet been established. Another alternative is to follow the Uniform Building Code for the region. According to it the SSCL is in a zone zero region for earthquake occurrence and buildings only need to be designed to a minimum static base shear. Again to be consistent with the conservative design approach the structure may exceed the chosen materials yield point when subjected to the response spectrum but the maximum stress values must be below 60% of the material ultimate strength. For our previous example of A36 this would be 42,000 psi. The earthquake should be applied to the operational mode and the maintenance mode.

The last criteria concerns the response of the CDS structure caused by ambient floor vibration. The magnitude and frequency content of the floor vibration in the GEM detector hall are unknown. However, two vibration envelopes were used as an estimate of the floor vibration, and the response of the CDS was calculated for both envelopes.

The first envelope was a simple function having a constant acceleration power spectral density (PSD) up to 10 Hz and uniform attenuation above 10 Hz. The second envelope was derived from measurements taken at a Los Alamos proton accelerator facility. The two envelopes are shown in Fig. 4. The envelopes differ significantly in the low frequency range (less than 10 Hz). Because the dominant natural modes of the CDS structure are in the vicinity of 1 Hz, the response of the structure to the two envelopes was significantly different. The design envelope from the LANL facility was chosen for this analysis because of the uncertainty in the shape of the constant power acceleration PSD in the low frequency range. A better estimate of the site-specific low frequency floor motion is needed.

The maximum allowable deflection of the tracker support points in the X or Y direction is considered to 10 microns (absolute). The maximum allowable rotational deflection of the tracker support points about the X axis is considered to be 0.5 milliradian.

Baseline Description

The present baseline for CDS describes two segmented disks 4 inches thick separated by .5m. The disks are composed of 16 segments which are assembled at the SSCL prior to installation into the detector hall. The structure is completely free standing, i.e. it does not derive any structural support from the magnet. There are no mechanisms for reinforcement of the calorimeter to the CDS (no gussets). The CDS is supported at the bottom between the magnet legs and then stabilized in the beam line direction by legs outside the magnet outer diameter.

The current version of the structure being analyzed is two 2 inch thick steel disks separated by .6m from the midplane of the plates. It still is supported at the bottom of the structure and stabilized in Z with legs on the magnet outside diameter. It is still comprised of 16 segments which will be assembled during calorimeter installation. Utilities for the central detectors will be fed through the space between the disks.

No determination on the ferromagnetic properties of the CDS material except for gussets. So for the baseline low carbon steel has been adopted.

Finite Element Model and Analysis Description

Figures 1 and 2 show the finite element model of the CDS. The mesh is much finer than in previous models. The model is broken at the mid plane of symmetry for computational efficiency. The entire model uses 4 node quadrilateral linear plate elements. The disks of the CDS are modeled with steel material properties and 2 inches thick. The cylinder which represents the calorimeters are modeled as 2 inch thick aluminum with a density which gives the calorimeter weight of 2200 Mg. The joint between the calorimeter is assumed to perfectly rigid joint. The bases of the legs are fixed in all degrees of freedom and symmetry boundary conditions are applied to the plane of symmetry for all the static solutions. For the buckling, earthquake, and ambient vibration solutions symmetric and anti symmetric boundary conditions were applied to the symmetry plane and the results combined accordingly. The model was analyzed using the Abaqus finite element code and run on a Cray YMP.

Results

For each of the load cases described above, stresses in every element and deflections of every node were calculated. The stresses given in this report are von Mises stresses (a combination of the principal stresses that is directly related to the distortion energy failure criterion for ductile materials).

The stress reported for each load case is the largest stress in the whole model; in most cases the peak stresses occur in a localized region and could potentially be reduced with localized reinforcement.

The maximum stresses caused by the static load cases are given in Table 1. In these load cases, the CDS was free standing, i.e., no Z direction support from the magnet halves. The CDS was analyzed both in the operating configuration (all calorimeters in place) and in a maintenance configuration where one end cap calorimeter was removed.

Table 1.
Static Load Cases

Load Case	Description	Maximum von Mises stress in model
1a	Both end cap calorimeters, free standing structure, no gussets.	4,700 psi
2a	One end cap calorimeter removed, free standing structure, no gussets.	17,300 psi
10a	One end calorimeter, free standing structure, 4 gussets, 2 oriented vertically and 2 oriented horizontally.	8,000 psi (membrane) 25,000 psi (gusset/calorimeter interface)
12a	One end cap calorimeter, free standing structure, 4 gussets oriented 45 degrees from vertical.	16,000 psi (membrane) 10,500 psi (gusset/calorimeter interface)

The elastic stability of the CDS was considered in the static buckling load cases. In these analyses, the critical load (the load at which the first static buckling occurs) was estimated for various applied loading and structural configurations. Table 2 gives the critical load computed for the operational configuration and the maintenance configuration.

Table 2
Static Buckling Load Cases

Load Case	Description	Critical Load, expressed as a multiple of the dead load

5a	Both end cap calorimeters, free standing structure.	Pcrit=15.9*dead load
5c	One end cap calorimeter, free standing structure.	Pcrit=10.5*dead load
11c	One end cap calorimeter, free standing structure, 4 gussets 2 oriented vertically and 2 oriented horizontally.	Pcrit=1.67*dead load
13a	One end cap calorimeter, free standing structure, 4 gussets oriented 45 degrees from vertical.	Pcrit=9.7* dead load

The response of the CDS to an earthquake was considered in the earthquake load cases. The primary earthquake that was considered was the Comanche Peak safe shutdown earthquake (figure 3), a seismic event used for certain design purposes at a nearby nuclear power plant. A static acceleration of 0.1 g in the direction of the beam was applied as a simple comparison.

In addition to the free standing operational and maintenance configurations the structure was analyzed in the operational mode with structural support from the magnet and in the maintenance configuration with a temporary support under the calorimeter to support the overturning moment caused by the missing end cap. The stiffness of the magnet was estimated by calculating the spring constant in the beam direction based on a fundamental frequency of 4.5 Hz and a weight of 1500 Mg.

In all cases, the earthquake ground motion was taken to be primarily in the Z direction (parallel to the beam) and secondarily in the vertical direction (at a magnitude of 2/3 of the Z direction component).

Table 3
Earthquake Load Case

Load Case	Description	Maximum von Mises stress in the model
7a	Both end cap calorimeters, free standing structure	22,700 psi
7b	One end cap calorimeter, free standing structure	35,337 psi

7c	Both end cap calorimeters, membrane restrained by magnet halves.	19,867 psi
7e	Both end cap calorimeters, temporary calorimeter support structure in place (both sides).	15,000 psi
7f	One end cap calorimeter, temporary calorimeter support structure in place (both sides).	14,000 psi
1c	Both end caps, 0.1 g static acceleration (in direction of beam), free standing structure.	10,400 psi
10b	One end cap calorimeter, free standing structure, 4 gussets, 2 oriented vertically and 2 horizontally.	16,000 psi (membrane) 48,000 psi (gusset/calorimeter interface)
12a	One end cap calorimeter, free standing structure 4 gussets 45 degrees form vertical.	22,000 psi (membrane) 18,000 psi (gusset/calorimeter interface)

The response of several on the calorimeter housing was calculated when the CDS base was subjected to ambient vibration. The floor motion envelope based on data measured at an accelerator facility in Los Alamos was used as excitation (figure 4). The spectrum was applied in X, Y, and Z directions.

Table 4
Random Ambient Vibration
Stability

Load Case	LANL Design PSD Envelope	RMS Deflection at the tracker relative to the base
8a	Z Direction Excitation X Direction response	0.009 micron

8a	Z Direction Excitation Y Direction Excitation	0.009 micron
8a	Z Direction Excitation Z Direction Response	0.287 micron
8a	Z Direction Excitation Theta X Response	0.0346 micro radian

For the operating mode the maximum von Mises stress is 4700 psi in both the no gusset and gusset version of the model. The maximum stress in the maintenance mode no gusset model is 17,000 psi while in the gusset model the maximum stress is 25,000 for gussets oriented vertically and horizontally and 16,000 psi for four gussets oriented 45 degrees form the vertical axis. The maximum stresses occur at the calorimeter-membrane interface for the no gusset model for both the operating configuration and the maintenance configuration. When gussets are added, regardless of orientation, the maximum stresses are redistributed from the calorimeter-membrane joint to the calorimeter-gusset joint for the operating configuration or the gusset-membrane joint for the maintenance configuration. For the four gusset model (oriented vertically and horizontally) the maximum stress is 25,000 psi which exceeds the 50% yield strength for A36 structural steel.

The minimum buckling eigenvalue of 1.67 times the dead load is in the four gusset model, 2 gussets oriented vertically and 2 oriented horizontally, during the maintenance mode. Buckling happens in the gusset under the calorimeter opposite the removed end cap. When the gusset orientation is rotated 45 degrees the buckling eigenvalue increases to 9.7 times the dead load in the maintenance mode. For the no gusset model the minimum buckling eigenvalue is 10.5 times the dead load in the maintenance mode and 15.9 times the dead load in the operating mode.

The earthquake scenario posed the harshest conditions on the central support. For the earthquake analysis the maximum stress happens during the maintenance mode regardless of whether gussets are present or not. The maximum stress for no gussets is 35,000 psi and 48,000 psi when gussets are present and oriented vertically and horizontally, and 22,000 psi when the gusset orientation is 45 degrees from the vertical axis. Again the maximum stresses are redistributed form the calorimeter-membrane joint to the gusset-membrane interface when gussets are added. During the operational mode the maximum stress is 22,700 psi in the no gusset free standing model. The stress is reduced to almost 20,000 psi when the CDS is allowed to have structural support from the magnet halves. The results are similar with gussets in the operational mode. When a temporary support structure is added under the calorimeter the maximum stress is reduced to 15,000 psi for the operational mode and 14,000 psi for the maintenance mode.

For the random ambient vibration stability the maximum response of points on the structure happened when the excitation was input in the beam direction. The rms X and Y response is .009 micron and the Z rms response is .287 micron. The rotation about the X axis is 0.0346 micro radian. All these responses are well below the design specifications and do not pose a significant design problem. The results are very dependent on the chosen input spectrum. If the accepted design input spectra is significantly different than the one used in this study the analysis should be repeated.

Recommendations

Based on the analyses performed a free standing CDS with no gussets meets all the minimum requirements set forth in this report for the operational and maintenance modes. Caution should be exercised when relying solely on the CDS during maintenance because of the high stresses calculated during an earthquake. It is recommended that installation of temporary support structures under both sides of the calorimeter be implemented as standard operating procedure anytime the magnet halves are withdrawn and personnel will be working in the detector hall around the central region. Temporary support structures should also be installed under both sides of the calorimeter anytime an end cap calorimeter is removed an during the entire time the end cap is removed.

The analysis also showed that the top portion of the CDS is virtually useless in a free standing no gusset scenario. For future work, more efficient structures as that shown in figure 5 should analyzed to help reduce the cost and weight.

Very little work has been completetd on the calorimeter-membrane joint design, yet the study clearly shoes this to be the most vulnerable portion of the structure. Completion of a working joint design along with a realistic assembly procedure should be a high priority in the coming year.

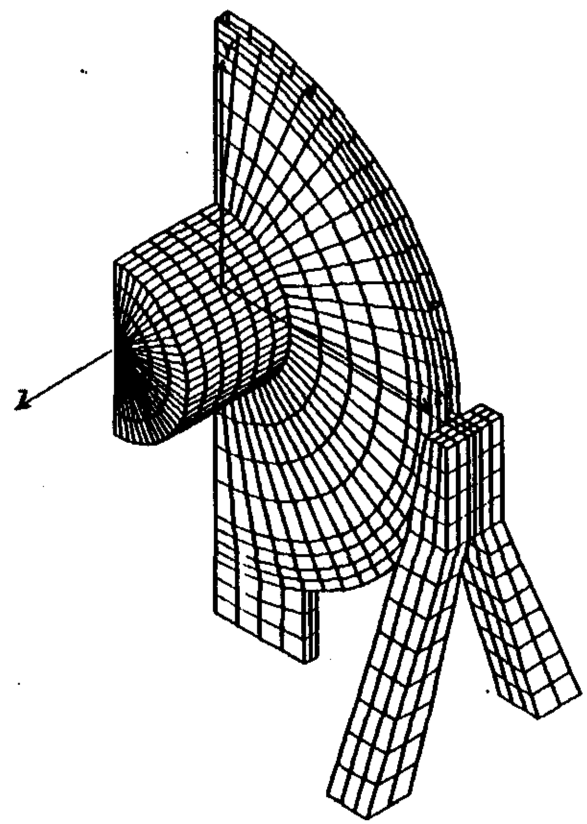


Figure 1: Symmetric Finite Element Model of the Central Detector Support.

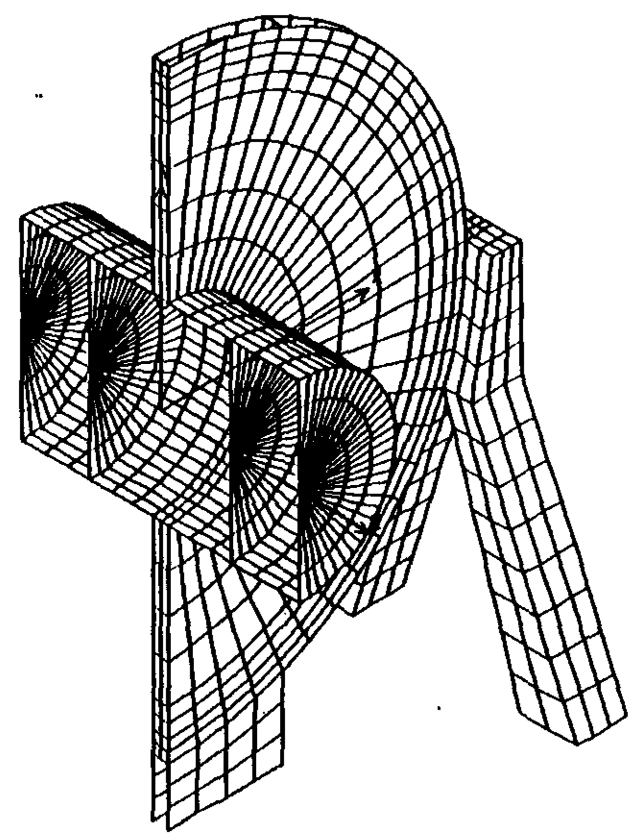


Figure 2: Symmetric Finite Element Model of the Central Detector Support.

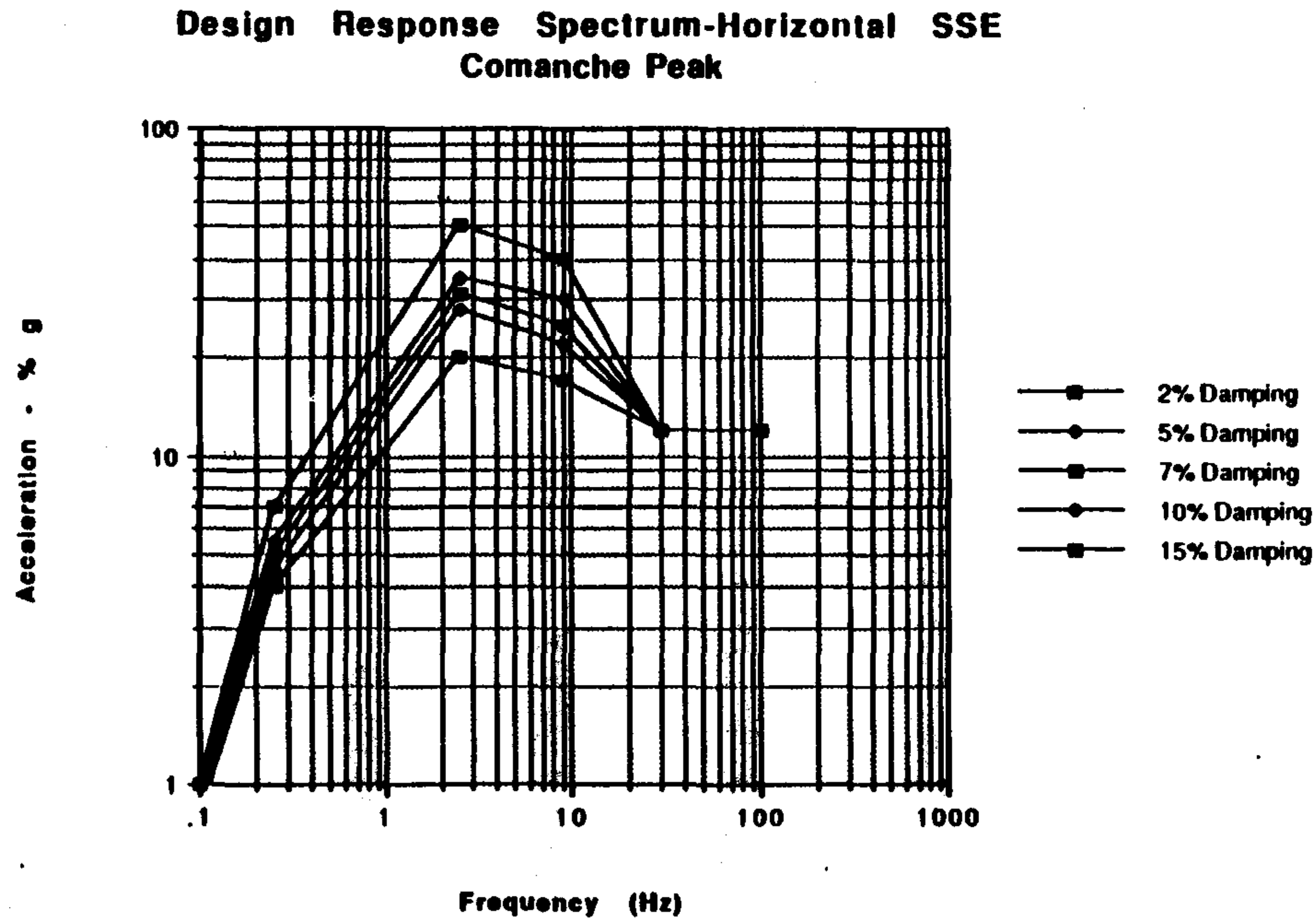
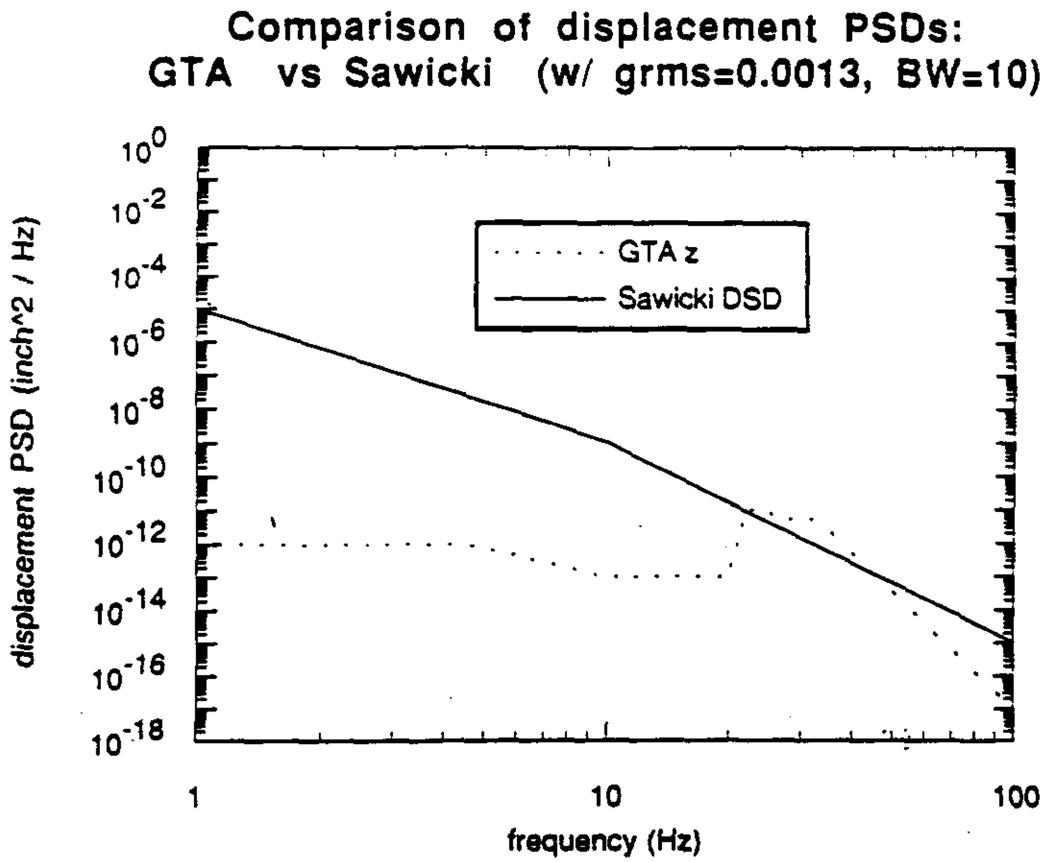


Figure 3: Safe Shutdown Design Response Spectrum Comanche Peak Steam Generating Plant.



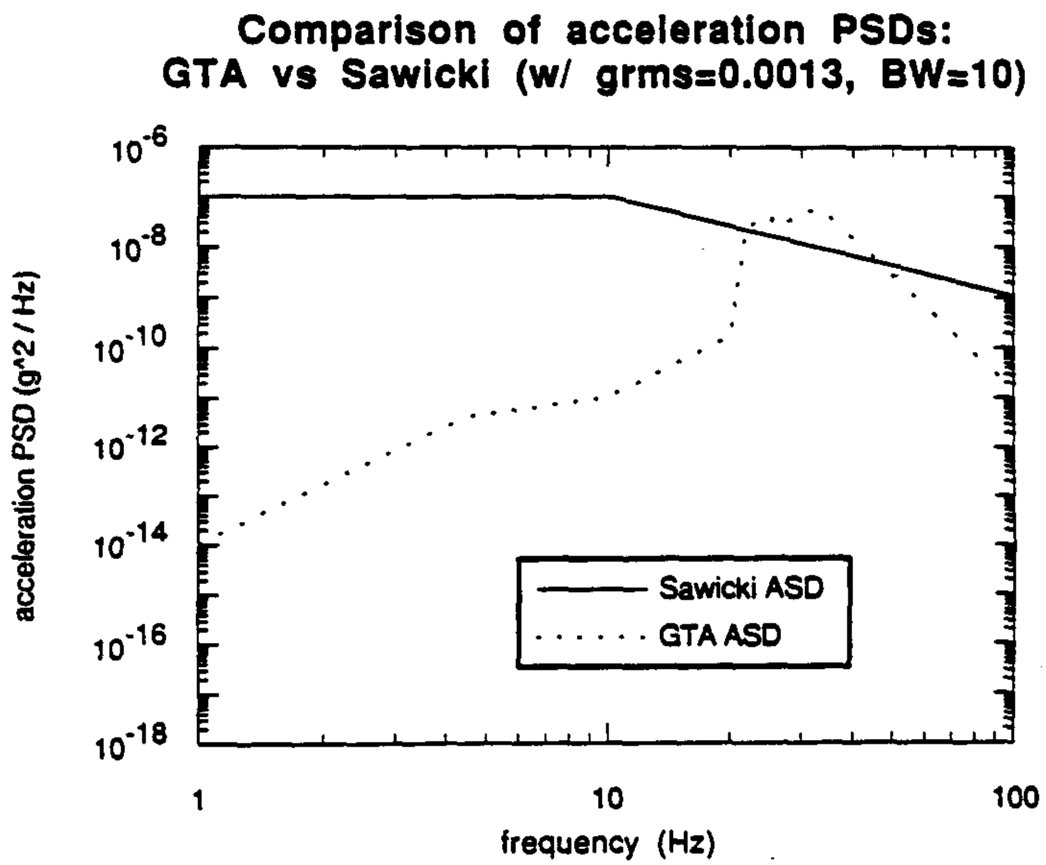


Figure 4: Comparison of the Proposed Ambient Vibration and LANL Measured Ambient Vibration Displacement PSD and Acceleration PSD.

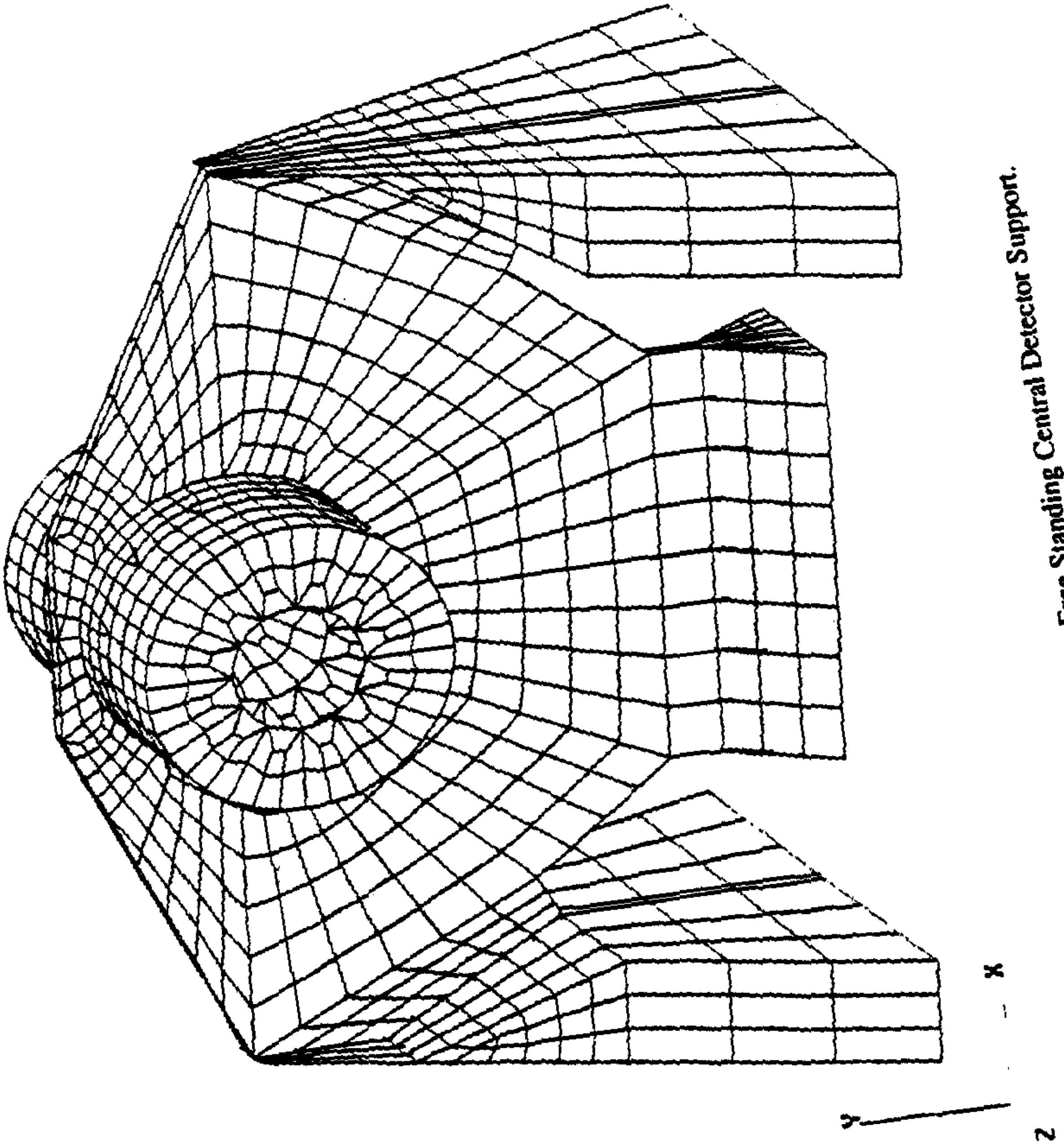


Figure 5: More Efficient Free Standing Central Detector Support.