HOPPER AND ASSOCIATES
ENGINEERS

FERMI 2 TURBINE FAILURE

POST EVENT EARTHQUAKE PASSIVE INSTRUMENTATION DATA EVALUATION

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1.0 INTRODUCTION

1.1 Fermi 2 History

The Enrico Fermi Unit 2 Nuclear Power Plant is a 1,203-MV gross Boiling Water Reactor located outside Detroit, Michigan on Lake Erie. Fermi 2 has been in commercial operation since 1988, using a turbine manufactured by English Electric of Rugby, England, now part of G.E.C.-Alsthom. The facility site is located on stable land, and few large intensity earthquakes have occurred in the facility vicinity throughout documented history.

1.2 Turbine Failure

At approximately 13:15 on December 25, 1993, the turbine at the Enrico Fermi Unit 2 Nuclear Power Plant failed. The turbine failure included thrown blades, severed cooling system piping, turbine lubricating system failures, and a hydrogen fire. Vibration imbalance in the main turbine generator activated a turbine alarm. Almost simultaneously, numerous alarms were received, including seismic event, additional turbine alarms, and reactor scram. Upon receiving the reactor scram alarm, the operator immediately began shutdown procedures of the turbine and reactor.

1.3 Shock Incident

Personal observations attest to a loud noise followed by a rumbling which lasted two to three minutes. The seismic event alarm and the reactor scram alarm were noticed concurrent with the loud noise and rumbling which was attributed to vibration.

The seismic event alarms are preset to activate at a 0.01 g level. This corresponds to the passive instrument sensitivity limit. The passive peak shock record plates in the sub-basement of the Reactor/Auxiliary building (HPCI room) recorded measurable accelerations. The passive peak shock record plates on the second and fifth floors of the Reactor/Auxiliary building did not record significant accelerations.

Instrumentation data from the passive sensors was evaluated and compared to those excitation levels in the Fermi 2 Updated Final Safety Analysis Report (UFSAR) to verify the continuing structural integrity of the Reactor/Auxiliary building and the equipment inside the building.

1.4 Result Summary

Globally, the Reactor/Auxiliary building did not experience an OBE event, and consequently, the building was never exercised near OBE excitation levels as evidenced by the insignificant accelerations measured on the second and fifth floors of the building. Likewise, the equipment on the second and higher floors was demonstrably never exercised near OBE excitation levels.

Below the second floor, the passive instrumentation exhibits OBE exceedences in the HPCI room. However, no anomalies were observed during the event, and inspections of both building and equipment after the event indicates there to be no apparent problems. Artificial time-histories developed to result in the passive instrumentation recorded response spectra exhibit those characteristics that would be anticipated from a surface wave system emanating from an impact at an adjacent surface location. These waves locally pass through the structural foundation with the path of the particle motion theoretically describing a single retrograde ellipse. They possess none of the energy characteristics of tectonic earthquake waves and do not result in the global structural excitation experienced during a traditional seismic event.

2.0 HISTORY

2.1 Seismic Events

2.1.1 Previous Seismic Events

Fermi 2 is located in a relatively seismic stable area. Approximately fifteen intensity VI (Modified Mercalli Scale) or greater earthquakes have occurred within a two hundred mile radius in the last two hundred years (Figure 2.1.1.1). Additionally, nine earthquakes of intensity V or less have occurred within a fifty mile radius of the facility (Figure 2.1.1.2). Although the Fermi 2 OBE is associated with an intensity VI seismic event, it is unlikely the facility will experience such an earthquake within its lifetime.

2.1.2 December 25, 1993

The National Geophysics Data Center and the National Oceanic and Atmospheric Administration show no seismic activity for December 25, 1993, within a five hundred km (310 mile) radius of Detroit. The center has immediate knowledge of all seismic activity in the Detroit vicinity of intensity III or greater.

The most recent seismic event within two hundred miles of the facility site had an intensity of approximately I and occurred in April of 1993. The passive peak shock recorder plates were calibrated and installed in July of 1993 (second and fifth floors) and September of 1993 (HPCI room). This evidence indicates the passive plate records contained only the turbine failure incident.

2.2 Sequence of Events

2.2.1 Turbine Failure and Damage

It is beyond the scope of this document to chronically arrange the events of the turbine failure on December 25, 1993.

At approximately 13:15 on December 25, 1993, the number 3 low-pressure turbine (LP3) at Fermi 2 failed catastrophically. The turbine threw five blades. One blade ripped through the steel turbine casing. Another blade was later retrieved from the condenser. The remaining blades are also believed to be inside the condenser. Vibration caused measurements in excess of 37.5 mils peak-to-peak at the turbine bearings, recorded by the Diagnostic Vibration Analysis (DVA) System.

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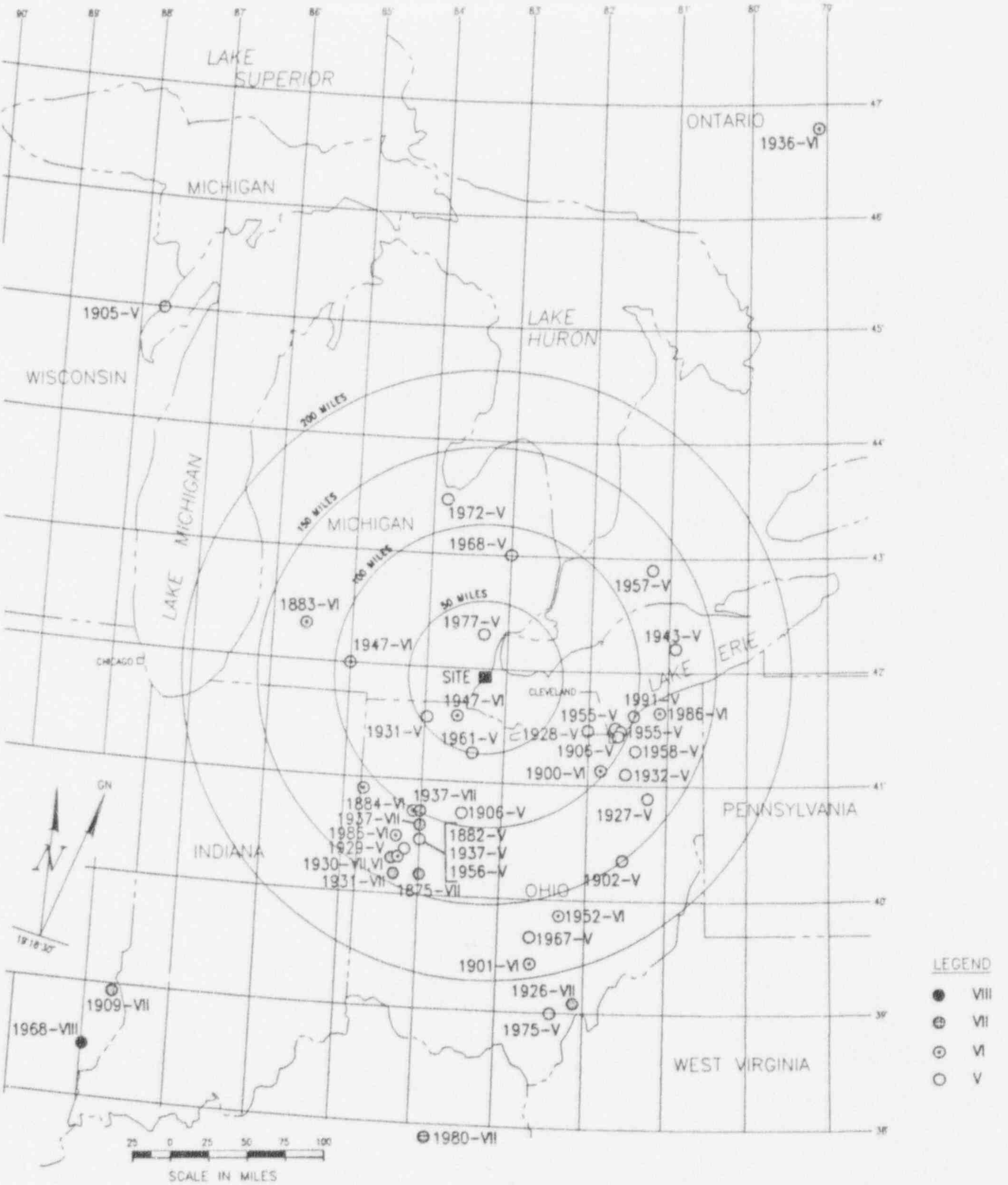
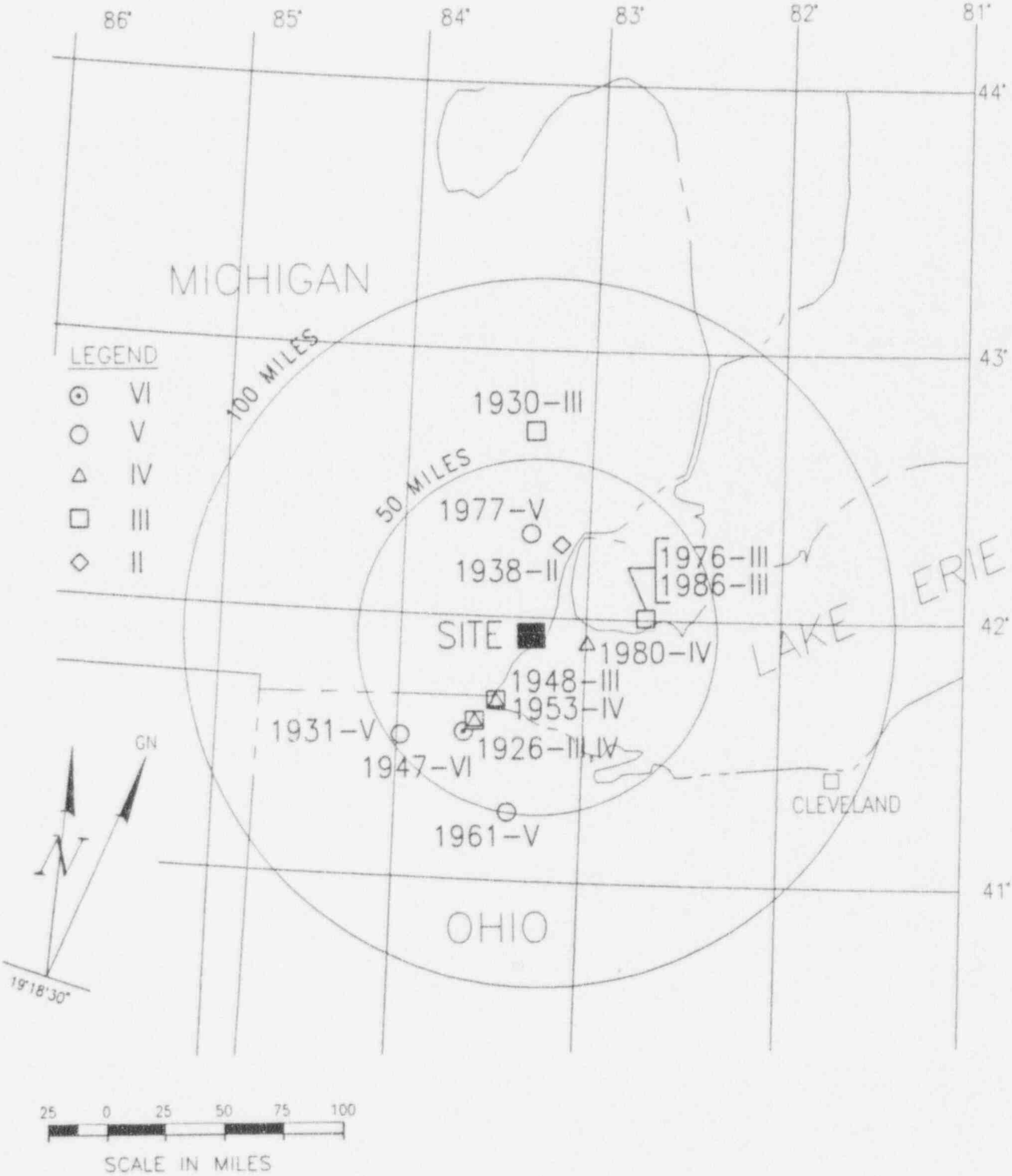


Epicenter Map, Detroit Area, Intensity V or Greater, 200 Mile Radius

Figure 2.1.1.1



Epicenter Map, Detroit Area, All Earthquakes, 50 Mile Radius

Figure 2.1.1.2

A small hydrogen fire occurred near the number 9 bearing, and the resulting fire charred the shield wall. The fire or the steam from the turbine casing activated the fire protection system. Approximately six hundred thousand gallons of water poured into the turbine building. Additionally, a 2" cooling system pipe was severed, adding more water. The turbine lubricating system also failed, and approximately seventeen thousand gallons of oil poured onto the floor. The ensuing mixture drained into the turbine building basement.

The turbine vibration tore couplings, sheared bolts, and loosened the excitor from the main turbine generator.

2.2.2 Shutdown

The turbine failure activated the turbine, seismic event, and reactor scram alarms, and both the turbine and the reactor proceeded to shutdown. All safety systems responded to achieve a satisfactory shutdown of the turbine and the reactor. The event was declared an alert at approximately 13:52 due to fire potential, and later downgraded to an unusual event.

2.2.3 Observations

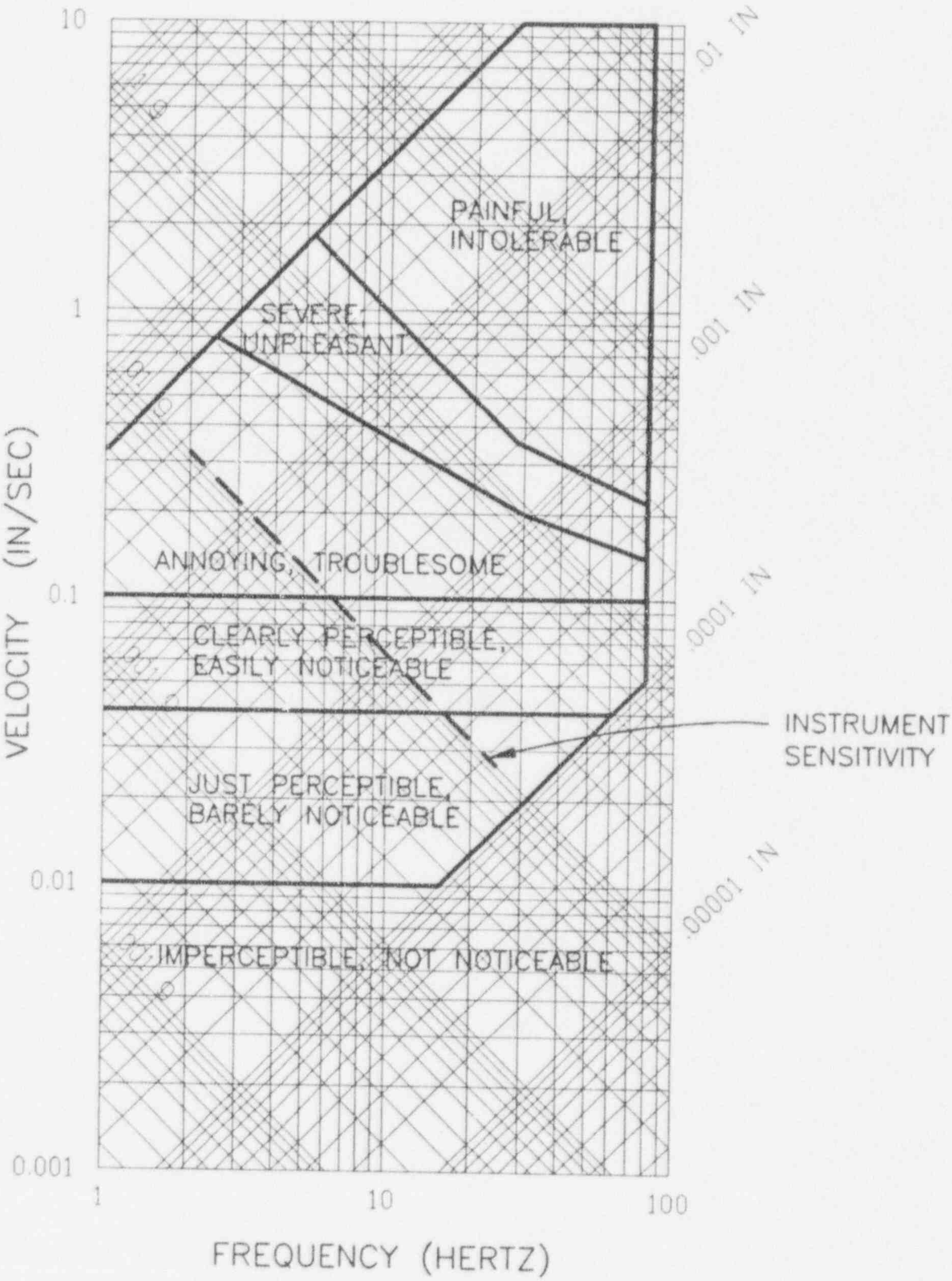
No personnel were in the vicinity of the turbine failure. Almost all personnel nearby heard a loud noise, followed by a rumbling, which lasted two to three minutes. Some personnel felt vibrations through the building. Almost simultaneously, personnel in the buildings heard the reactor scram alarm. Those near the turbine building reported heavy smoke.

Several personnel were directed to inspect the turbine building for fire. They noted damaged parts on the third floor, and a small fire at the generator brushes, which they extinguished with a CO2 fire extinguisher.

Remaining personnel proceeded in duties as directed to facilitate the reactor shutdown.

2.2.4 Human Sensitivity to Vibration

Work conducted by numerous researchers have established physiological limits of human perceptibility to vibration. The studies demonstrate humans can detect vibrations well below the current instrument sensitivity at Fermi 2 (Figure 2.2.4.1).



Human Vibration Sensitivity

Figure 2.2.4.1

3.0 DATA

3.1 Instrumentation and Location

Engdahl PSR1200 peak shock recorders are the passive recording instrumentation located in the Reactor/Auxiliary building. The sensors record various ground motion and in-structure response shock spectra in three orthogonal directions. The sensors contain twelve reeds, each with diamond tipped stylus, which etches a scribe mark on a metal record plate. Each reed is tuned to a predominant structural frequency, ranging from approximately two to twenty-five Hz. The record plate and the scribe mark provide a permanent indication of the dynamic excitation at a particular frequency. Reed deflection is calibrated as a linear function of acceleration. After a seismic event, the plates are removed and the reduced data establishes the response spectra.

Three Engdahl recorders are located in the Reactor/Auxiliary building, in the HPCI room, the second floor, and the fifth floor (Figures 3.1.1.1 through 3.1.1.3). The recorders are positioned to measure accelerations in the vertical, north/south, and east/west directions at each sensor.

Passive sensors are calibrated and the plates replaced after a seismic event or approximately every 18 months. The plates for the Reactor/Auxiliary building were last calibrated and replaced in July of 1993 on the second and fifth floors, and September of 1993 in the HPCI room.

3.2 Data Reduction

3.2.1 Passive Sensors - Response Spectra

The record plates from the three passive sensors in the Reactor/Auxiliary building were removed for data reduction. The plates were inspected for scribe marks, and the calculated accelerations were plotted against the relevant OBE and SSE response spectra (Tables 3.2.1.1 through 3.2.1.9 and Figures 3.2.1.1 through 3.2.1.9). Additionally, the instrument sensitivity was plotted. The passive sensor is capable of measuring accelerations greater than 0.01 g. The Engdahl peak shock recorders have 2% damping, and ± 3% accuracy at 1 g.

The sensors were last calibrated and the plates replaced in July of 1993 (second and fifth floors) and in September of 1993 (HPCI room).

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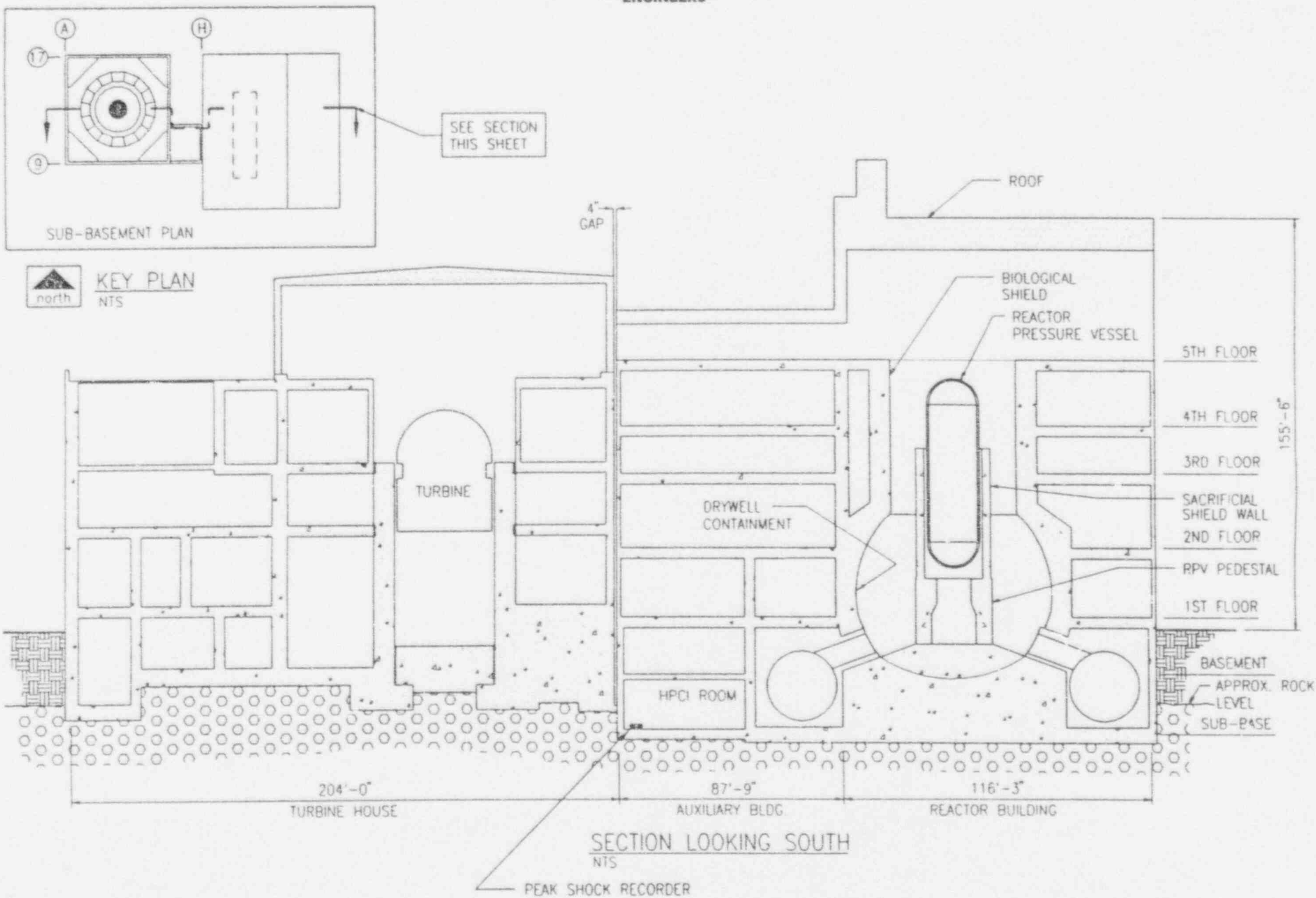
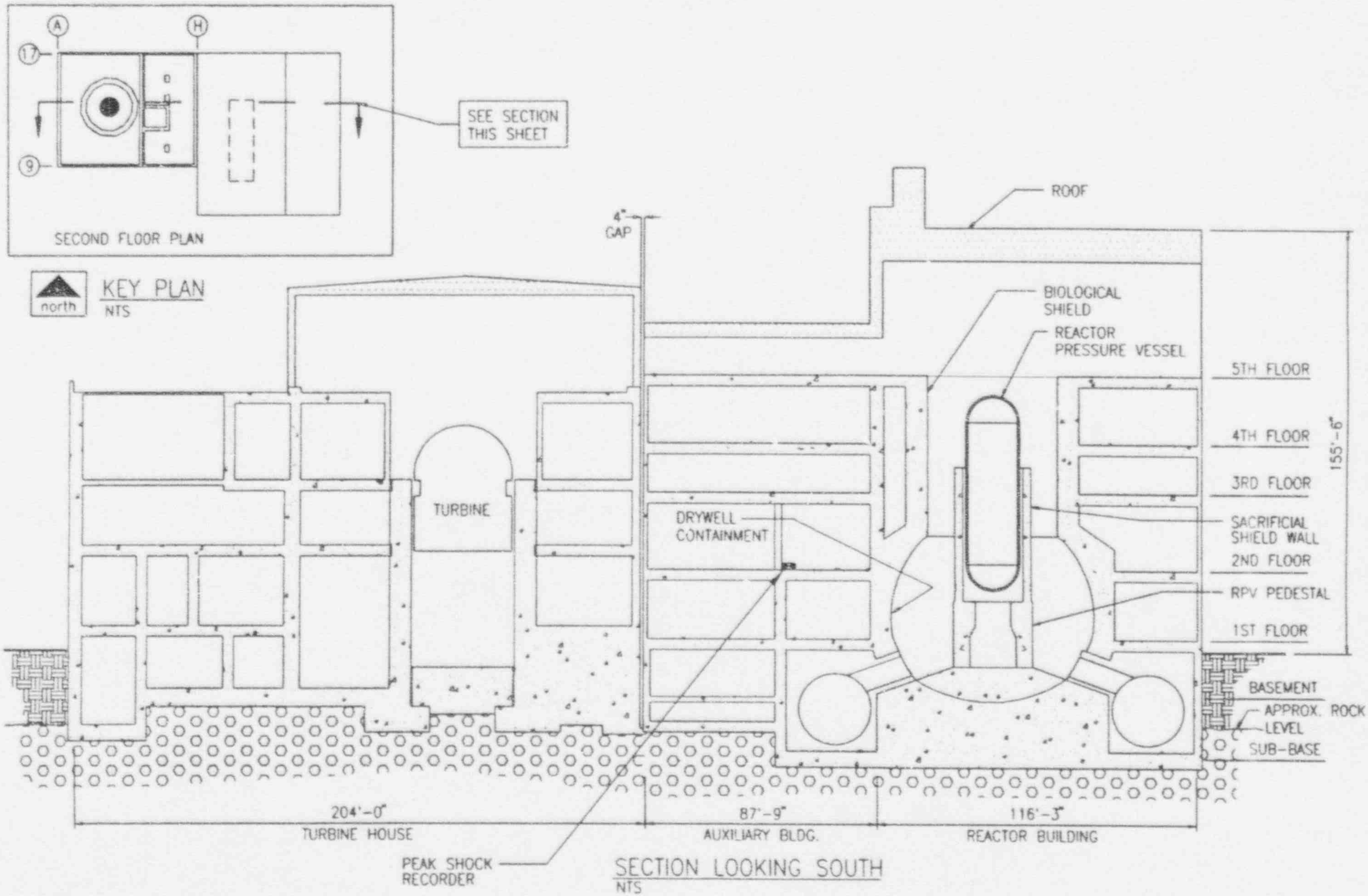
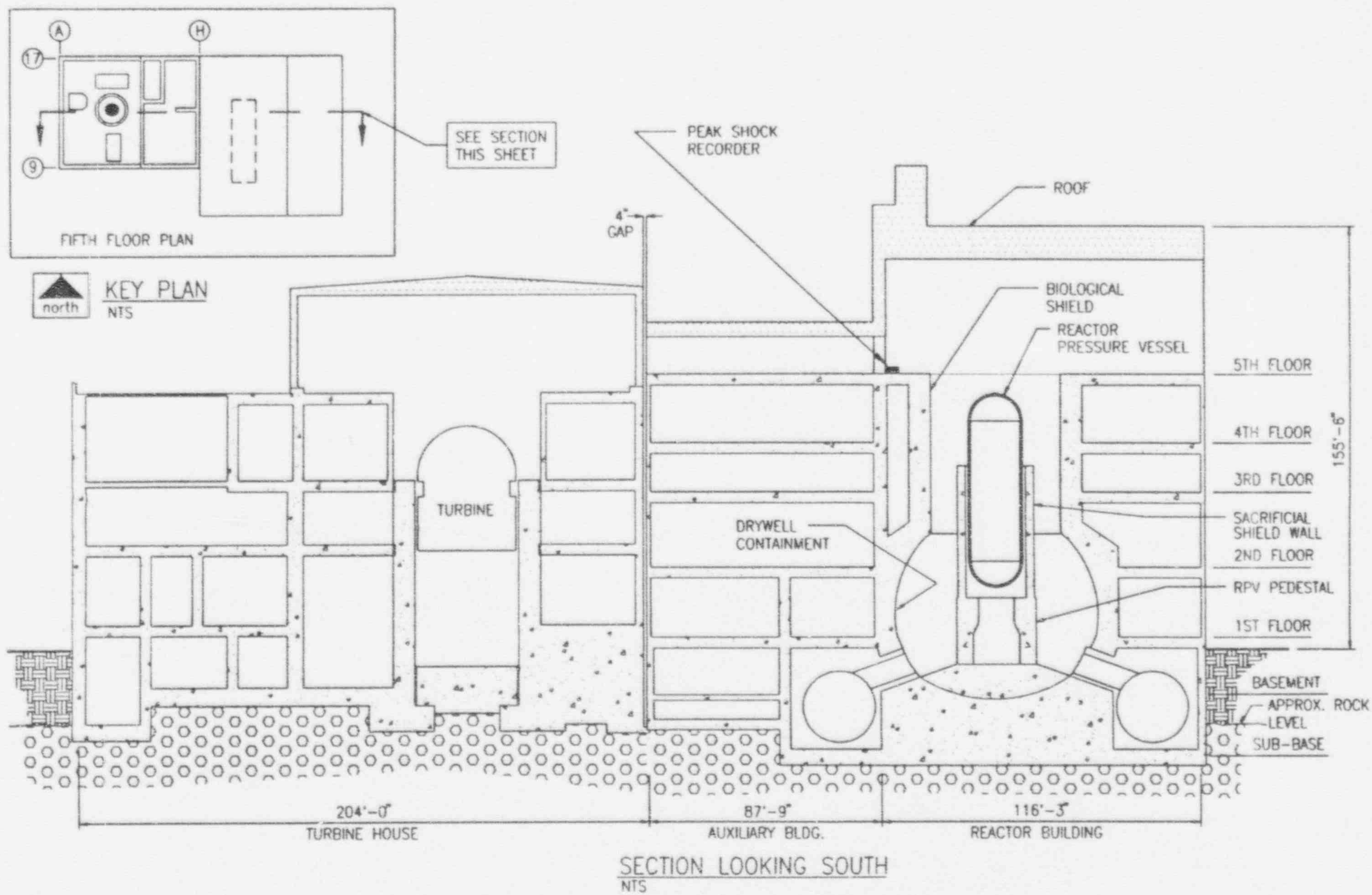


Passive Instrumentation Location at HPCI Room
Figure 3.1.1.1



Passive Instrumentation Location at Second Floor

Figure 3.1.1.2



Passive Instrumentation Location at Fifth Floor

Figure 3.1.1.3

Reed No.	Hz	Measured mm	Inch	g/Inch	g
1	2.11	2.5	0.098	0.349	0.034
2	2.54	4.25	0.167	0.528	0.088
3	3.45	4.5	0.177	0.865	0.153
4	4.07	6.25	0.25	1.24	0.31
5	5.1	2.5	0.10	1.98	0.19
6	6.36	1.0	0.04	3.14	0.12
7	7.95	0.25	0.01	5.18	0.05
8	10.16	0.25	0.01	7.26	0.07
9	12.75	0.5	0.02	13.61	0.27
10	15.58	0.25	0.01	18.10	0.18
11	20.33	-		30.66	
12	25.25	-		46.98	

D30-N005 Passive Instrumentation, Vertical Direction Records - HPCI Room

Table 3.2.1.1

Reed No.	Hz	Measured mm	Inch	g/Inch	g
1	2	-		0.357	
2	2.5	0.5	0.02	0.52	0.01
3	3.17	-		0.84	
4	4.15	-		1.35	
5	4.95	-		1.90	
6	6.4	-		3.26	
7	7.75	-		4.69	
8	9.8	1.0	0.04	7.38	0.29
9	12.65	-		12.39	
10	15.9	-		18.11	
11	20.29	-		29.40	
12	25.41	-		45.50	

D30-N005 Passive Instrumentation, North/South Direction Records - HPCI Room

Table 3.2.1.2

Reed No.	Hz	Measured mm	Inch	g/Inch	g
1	1.96	2.75	0.108	0.376	0.041
2	2.39	6.0	0.236	0.556	0.131
3	3.16	6.5	0.256	0.89	0.23
4	3.96	3.2	0.126	1.29	0.16
5	5.05	2.0	0.079	2.10	0.17
6	6.32	-		3.18	
7	7.9	3.25	0.128	4.86	0.62
8	9.89	-		7.58	
9	12.27	-		11.58	
10	15.7	0.5	0.02	18.87	0.37
11	19.67	1.5	0.059	30.08	1.78
12	25.71	-		48.78	

D30-N005 Passive Instrumentation, East/West Direction Records - HPCI Room

Table 3.2.1.3

Reed No.	Hz	Measured mm	Inch	g/Inch	g
1	2.05	-		0.322	
2	2.45	-		0.494	
3	3.21	-		0.784	
4	3.96	-		1.243	
5	4.86	-		1.918	
6	6.35	-		3.101	
7	7.84	-		4.9	
8	10.08	-		7.85	
9	12.59	-		11.7	
10	15.98	-		19.23	
11	20.49	-		29.85	
12	25.18	-		45.72	

D30-N601 Passive Instrumentation, Vertical Direction Records - Second Floor

Table 3.2.1.4

Reed No.	Hz	Measured mm	Inch	g/Inch	g
1	1.99	-		0.362	
2	2.59	0.13	**0.005**	0.536	**0.003**
3	3.11	-		0.821	
4	3.93	-		1.31	
5	5.03	-		1.99	
6	6.39	-		3.21	
7	7.96	-		4.86	
8	10.13	-		7.44	
9	12.54	-		12.31	
10	15.88	-		18.35	
11	19.91	-		28.73	
12	25.04	-		47.04	

D30-N601 Passive Instrumentation, North/South Direction Records - Second Floor

Table 3.2.1.5

Reed No.	Hz	Measured mm	Inch	g/Inch	g
1	2.14	-		0.372	
2	2.54	-		0.524	
3	3.29	-		0.831	
4	3.95	-		1.32	
5	5.12	-		1.95	
6	6.33	-		3.17	
7	7.78	-		4.82	
8	9.92	-		7.48	
9	12.91	-		12.27	
10	15.89	-		18.61	
11	20.19	-		29.63	
12	25.53	-		45.99	

D30-N601 Passive Instrumentation, East/West Direction Records - Second Floor

Table 3.2.1.6

Reed No.	Hz	Measured mm	Inch	g/Inch	g
1	2	-		0.306	
2	2.58	-		0.508	
3	3.25	0.15	0.006	0.819	0.005
4	4.05	-		1.29	
5	5.05	-		2.01	
6	6.5	-		3.16	
7	7.85	-		5.5	
8	9.8	-		7.06	
9	12.8	-		11.96	
10	15.8	-		20.42	
11	20.2	-		28.99	
12	25.2	-		44.42	

D30-N006 Passive Instrumentation, Vertical Direction Records - Fifth Floor

Table 3.2.1.7

Reed No.	Hz	Measured mm	Inch	g/Inch	g
1	2.14	-		0.4	
2	2.38	-		0.518	
3	3.2	-		0.843	
4	4	-		1.29	
5	5.1	-		2.07	
6	6.45	-		3.28	
7	7.95	-		4.84	
8	10.05	-		7.75	
9	12.57	0.13	**0.005**	11.90	**0.06**
10	15.7	-		19.05	
11	20.3	-		29.2	
12	25.2	-		47.07	

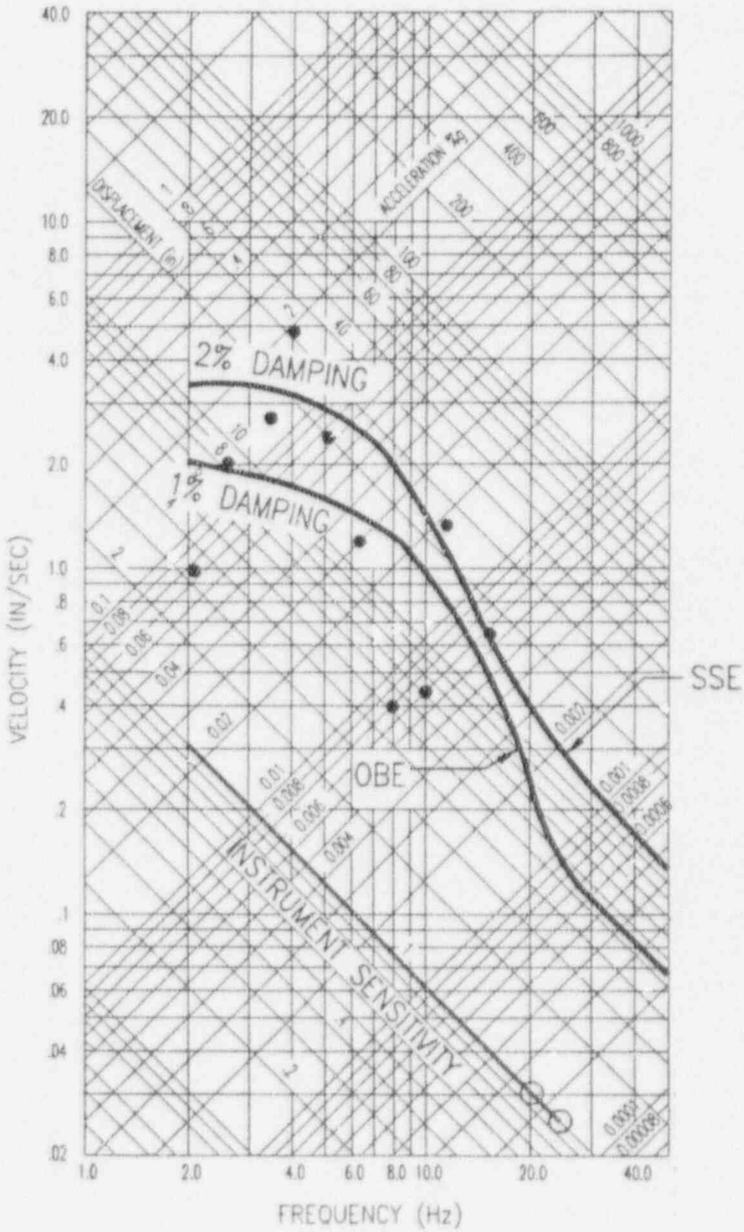
D30-N006 Passive Instrumentation, North/South Direction Records - Fifth Floor

Table 3.2.1.8

Reed No.	Hz	Measured mm	Inch	g/Inch	g
1	2.11	-		0.371	
2	2.58	-		0.522	
3	3.25	-		0.833	
4	4.15	-		1.33	
5	4.9	-		1.85	
6	6.3	0.25	0.01	3.11	0.03
7	7.9	-		4.84	
8	10.2	-		7.31	
9	12.5	-		11.68	
10	15.8	0.125	0.005	17.62	0.09
11	20.1	-		28.59	
12	25.1	-		48.21	

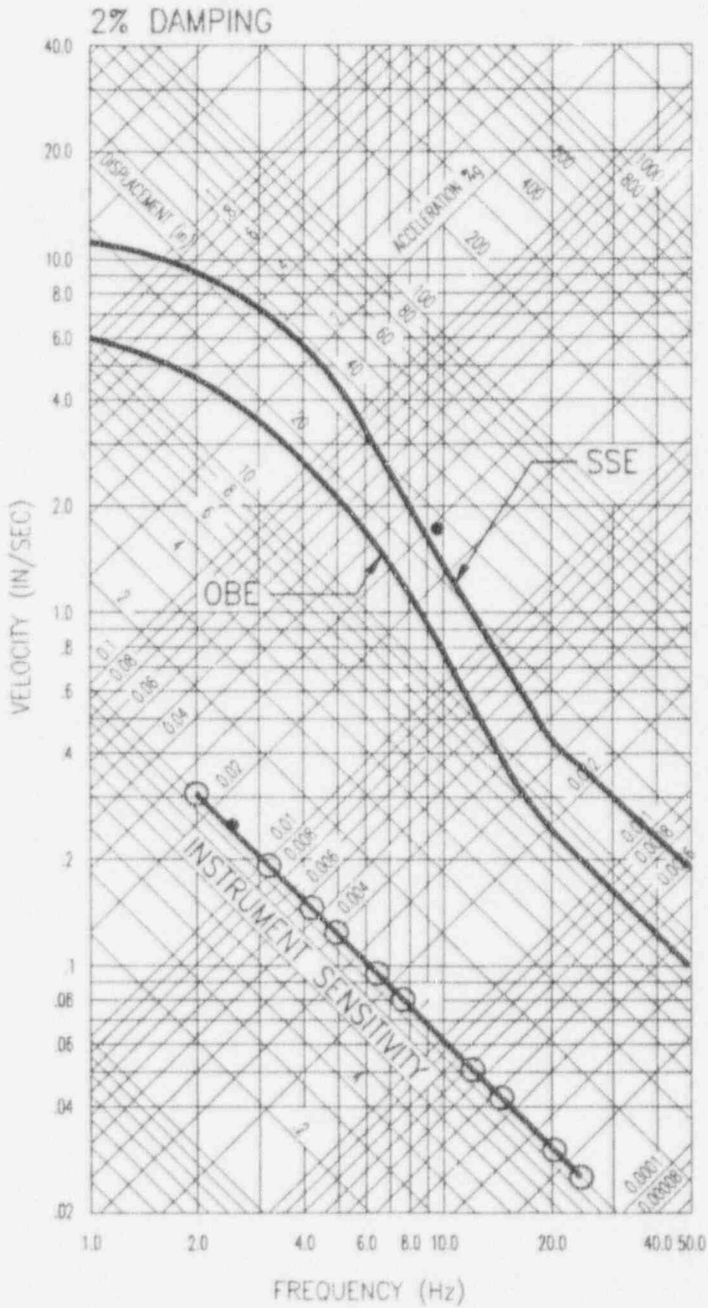
D30-N006 Passive Instrumentation, East/West Direction Records - Fifth Floor

Table 3.2.1.9



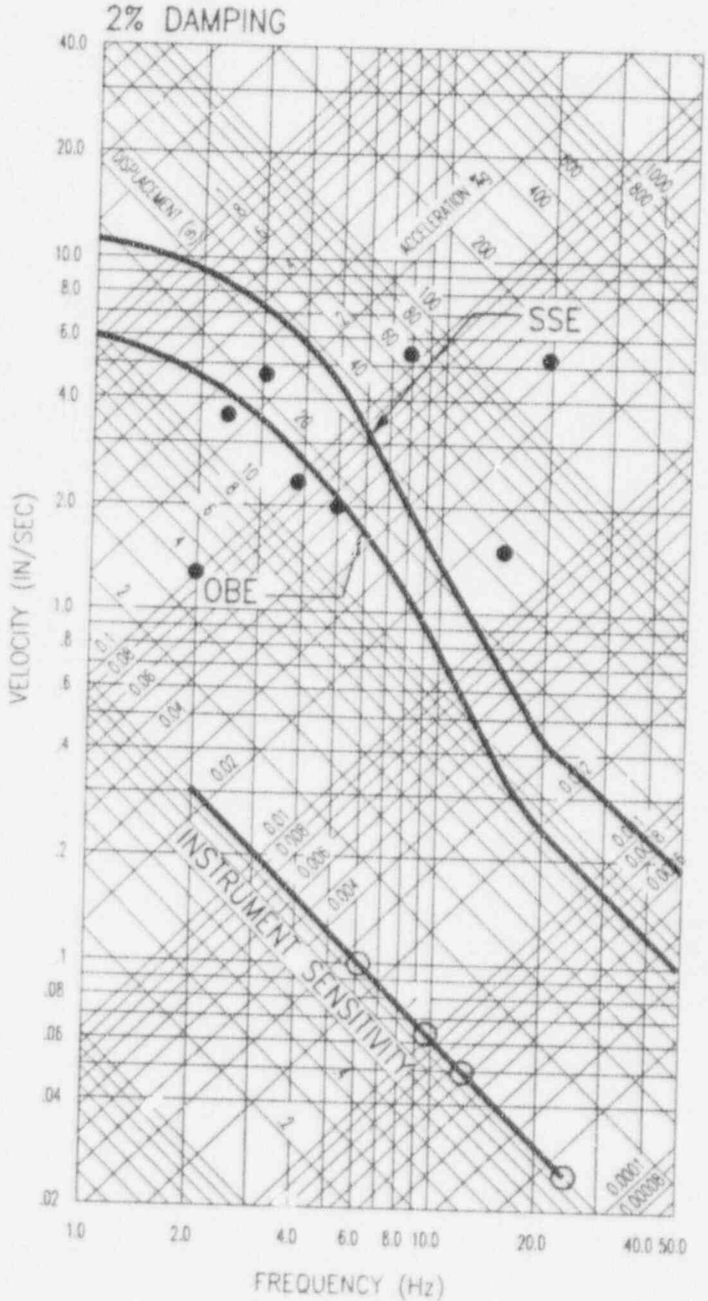
D30-N005 Passive Instrumentation, Vertical Response Spectra - HPCI Room

Figure 3.2.1.1



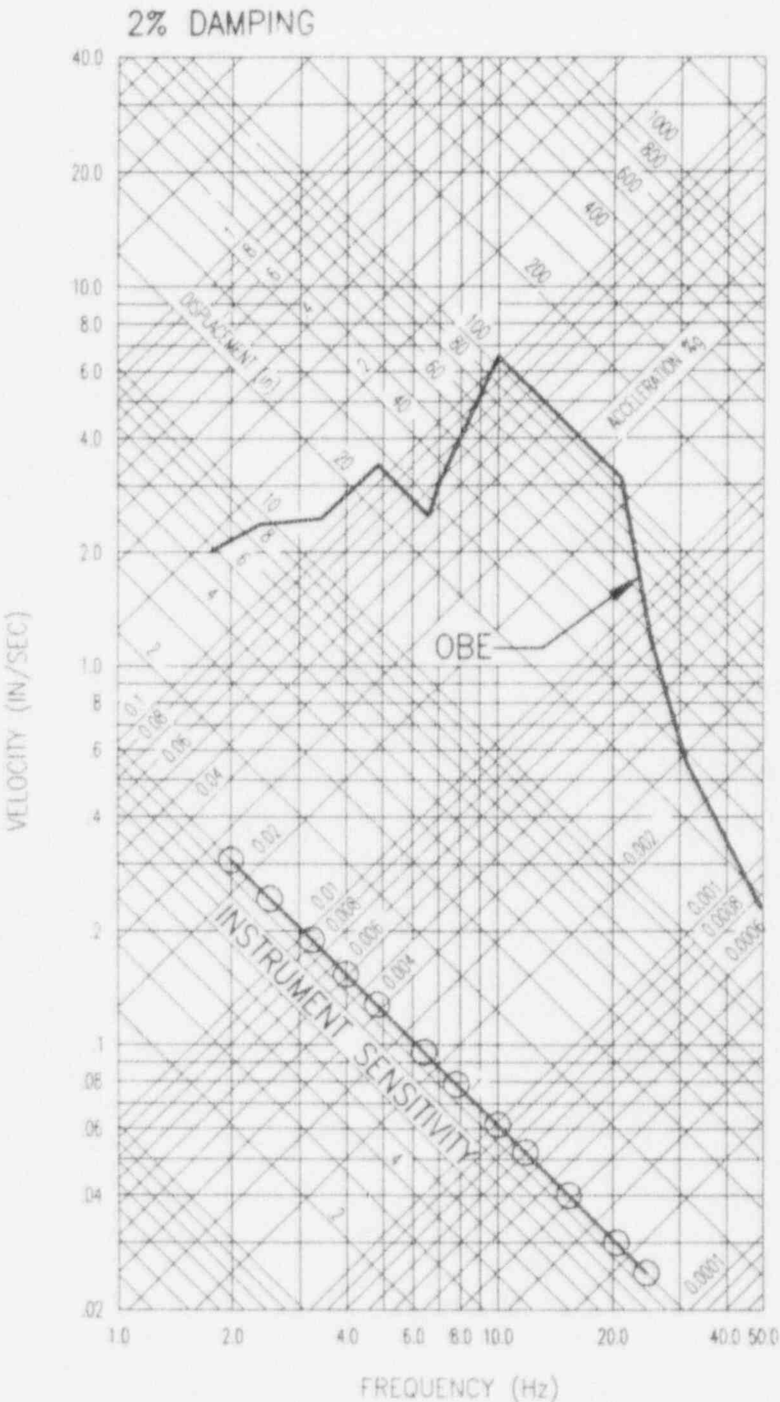
D30-N005 Passive Instrumentation, North/South Response Spectra - HPCI Room

Figure 3.2.1.2



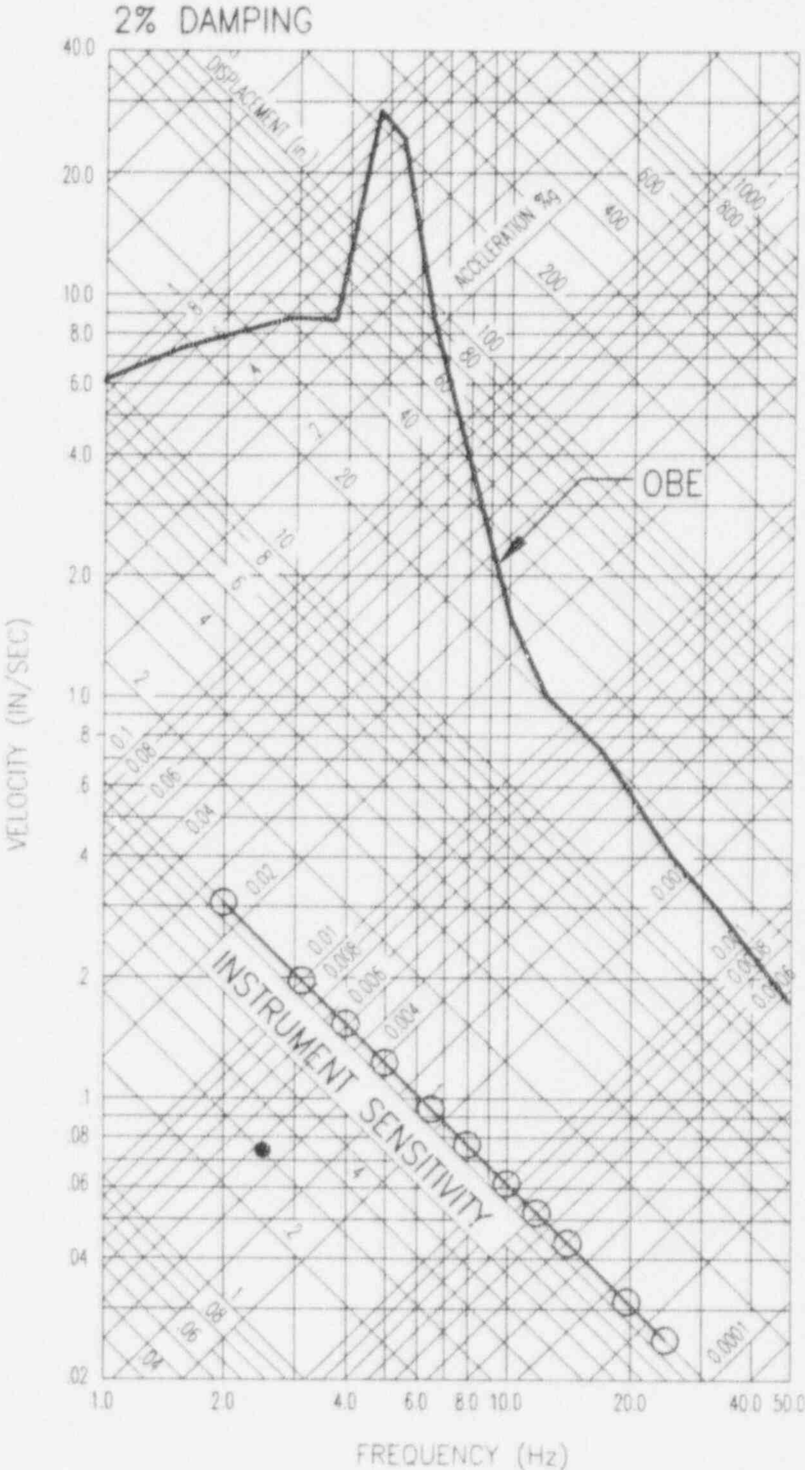
D30-N005 Passive Instrumentation, East/West Response Spectra - HPCI Room

Figure 3.2.1.3



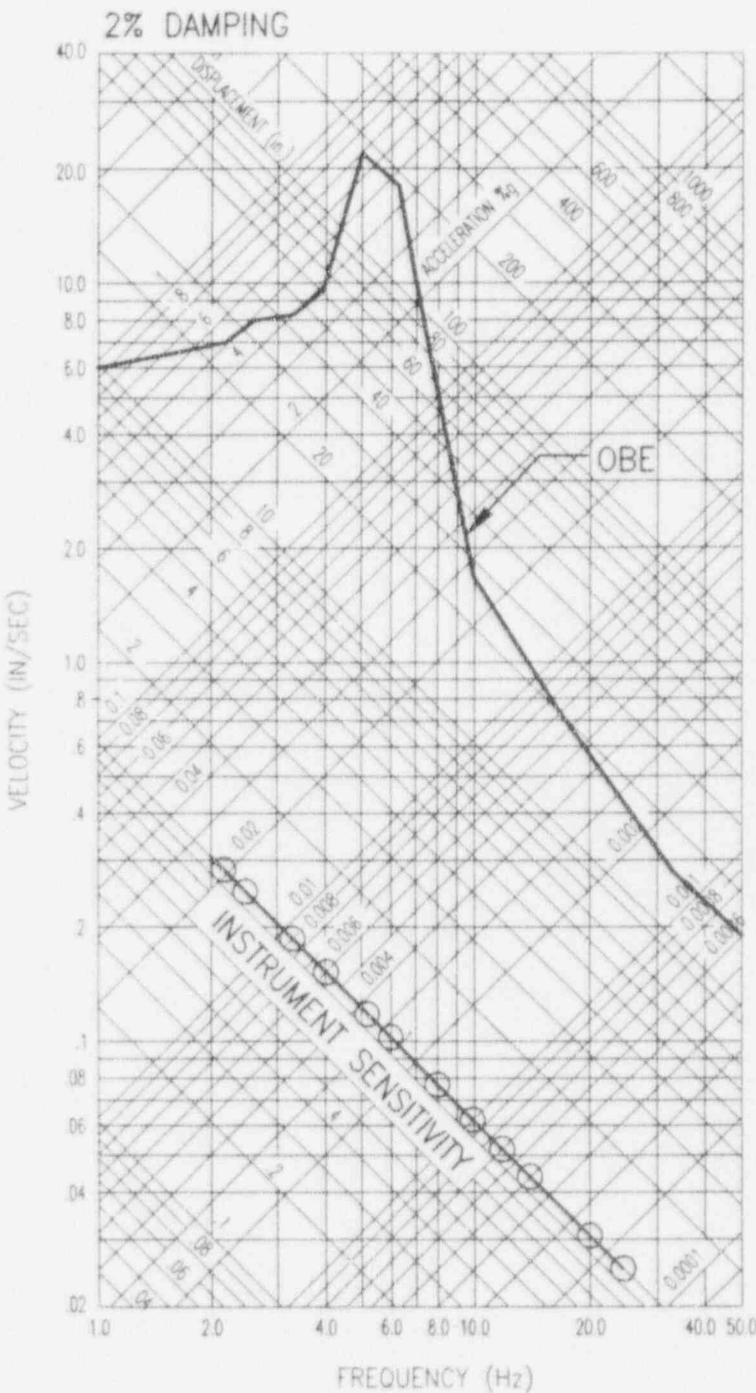
D30-N601 Passive Instrumentation, Vertical Response Spectra - Second Floor

Figure 3.2.1.4



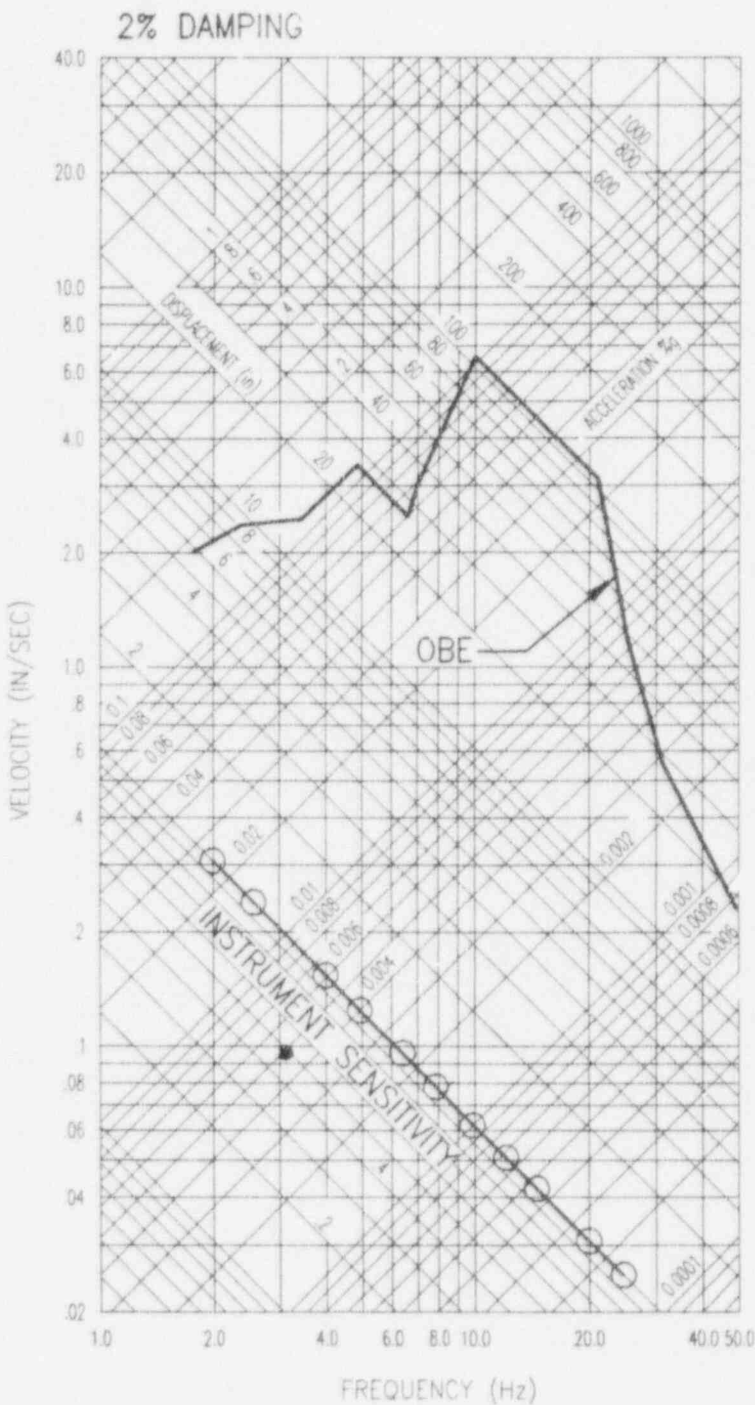
D30-N601 Passive Instrumentation, North/South Response Spectra - Second Floor

Figure 3.2.1.5



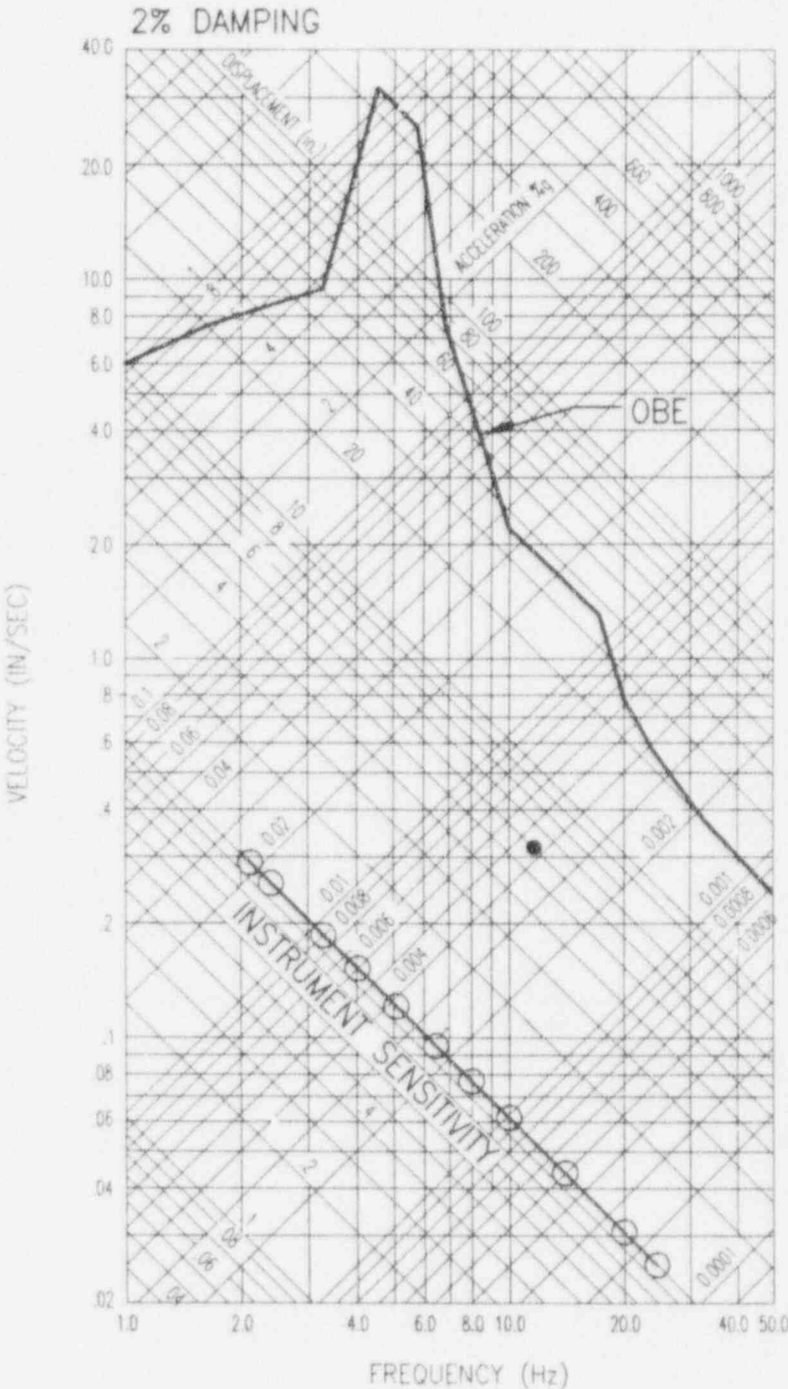
D30-N601 Passive Instrumentation, East/West Response Spectra - Second Floor

Figure 3.2.1.6



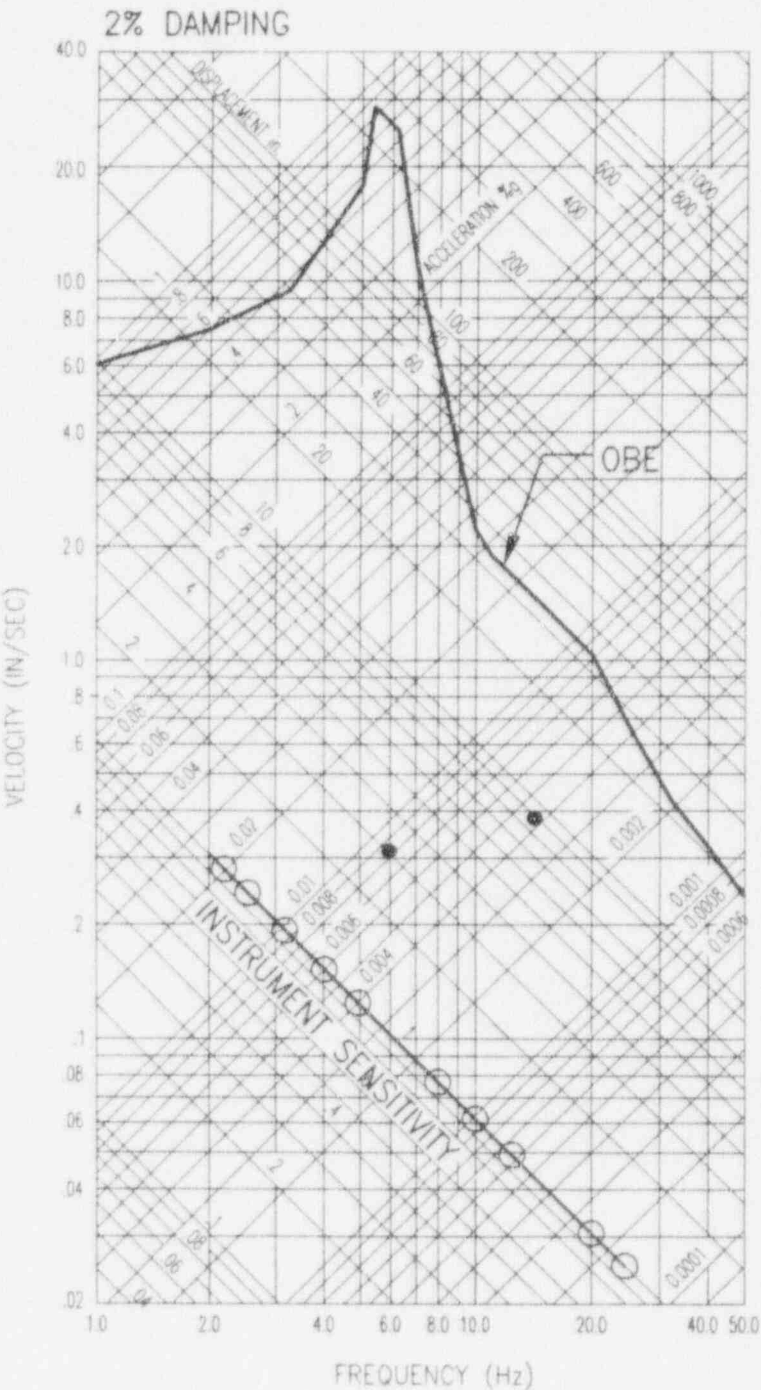
D30-N006 Passive Instrumentation, Vertical Response Spectra - Fifth Floor

Figure 3.2.1.7



D30-N006 Passive Instrumentation, North/South Response Spectra - Fifth Floor

Figure 3.2.1.8



D30-N006 Passive Instrumentation, East/West Response Spectra - Fifth Floor

Figure 3.2.1.9

3.2.2 Artificially Generated Time-History

A feasible time-history was generated to result in the measured response spectra by an iterative procedure. The procedure involved assuming a viable time-history obtained by a finite summation of harmonic excitations, from which a spectra was generated. Once this generated response spectra reasonably matched the measured response spectra, the corresponding time-history was established as the probable motion of the building foundation.

Only two passive instrumentation records contained enough significant data points for the above exercise. They are the east/west and vertical directions from the HPCI room.

The horizontal east/west direction response spectra produced a time-history which is representative of an impulse excitation. This time-history is shown in Figure 3.2.2.1. Figure 3.2.2.2 shows the measured and artificial response spectra.

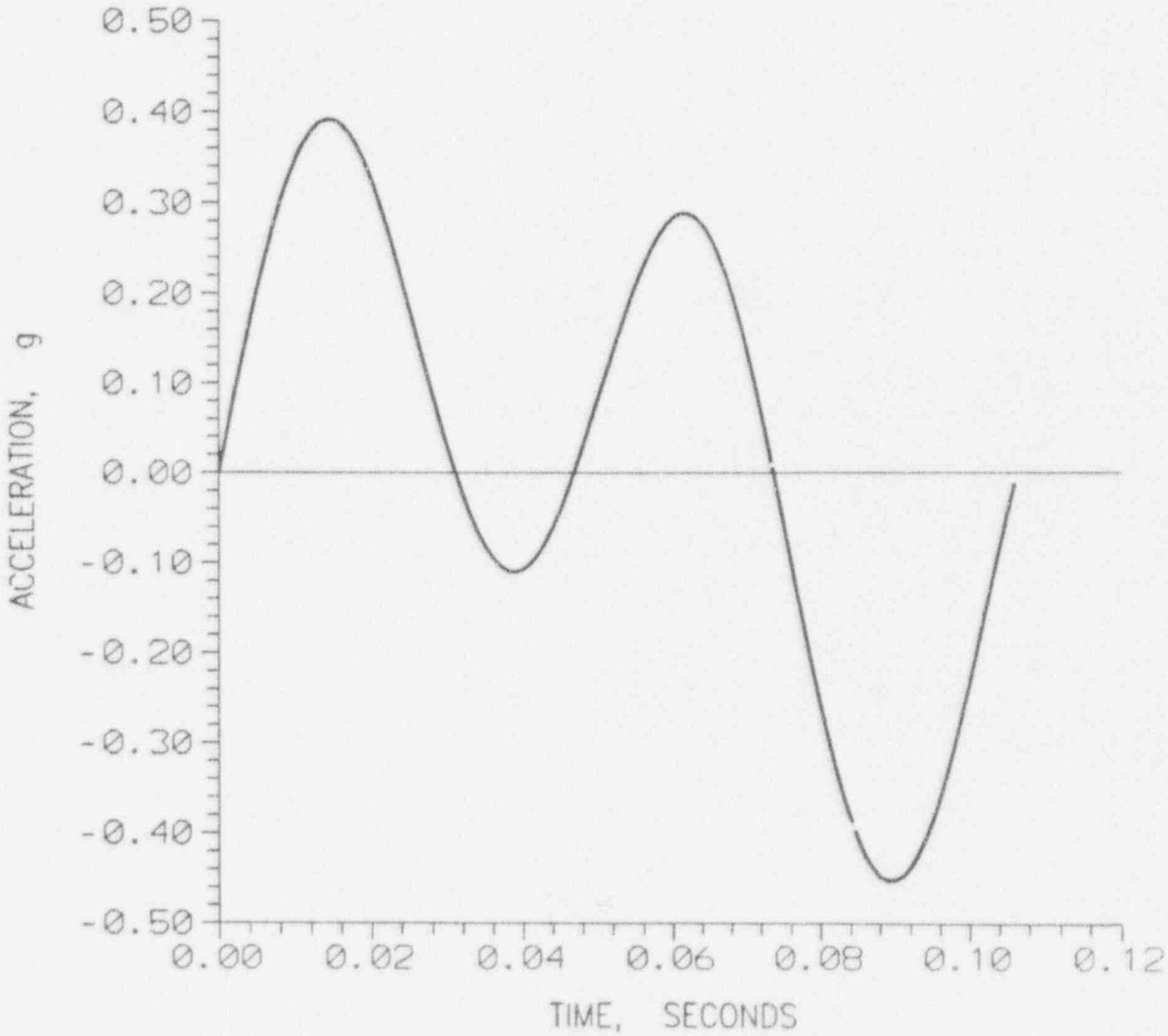
From the east/west artificial time-history, the vertical artificial time-history was generated based on typical Rayleigh wave characteristics and theory. The time-history is shown in Figure 3.2.2.3. Figure 3.2.2.4 shows the measured and artificial response spectra.

3.3 Results

The turbine failure on December 25, 1993, did not result in a significant Reactor/Auxiliary building dynamic excitation or a building global exceedence of the OBE. This was demonstrated by the insignificant accelerations recorded by the passive sensors on the second and fifth floors of the Reactor/Auxiliary building.

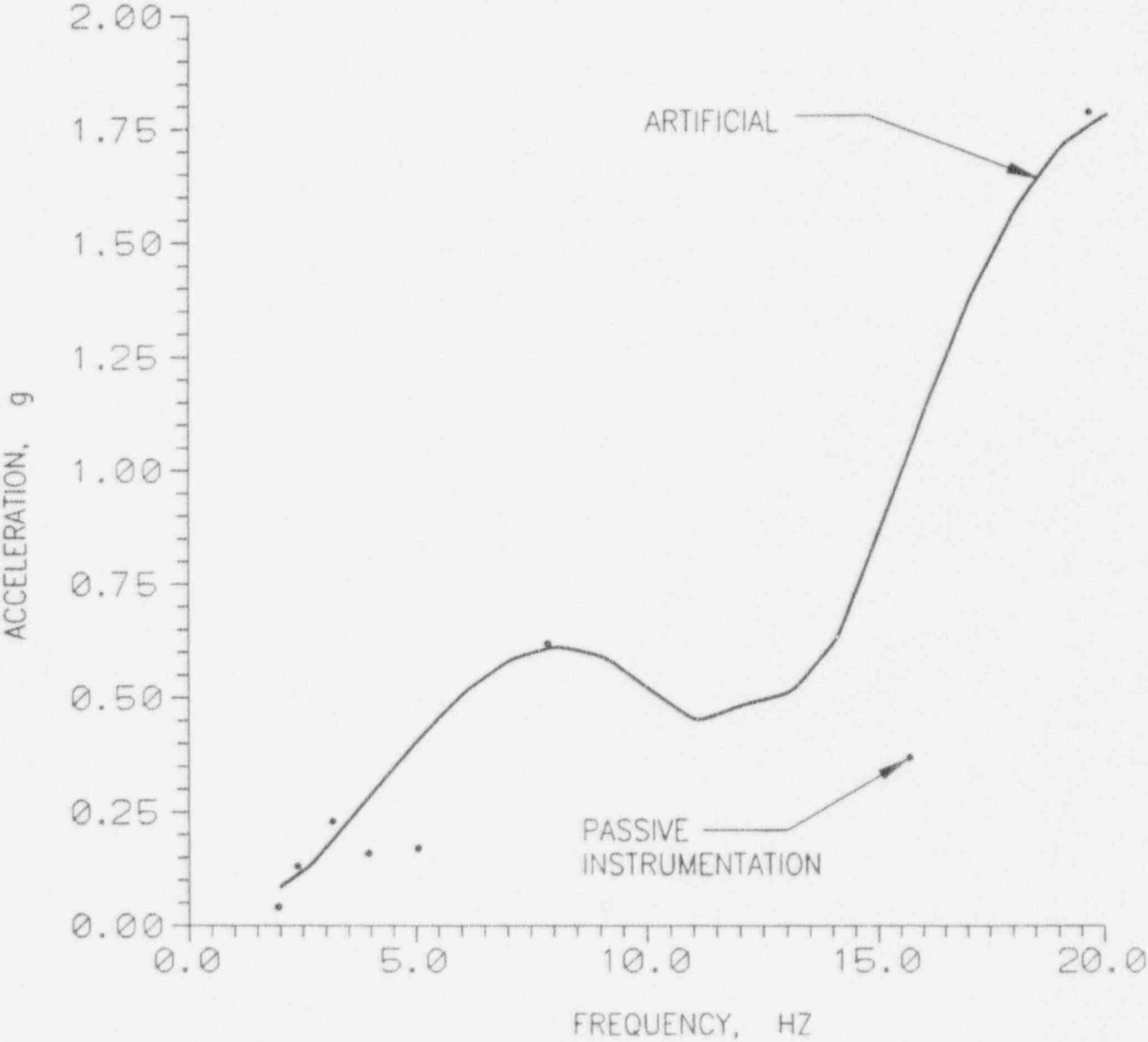
Below the second floor in the foundation, the building and equipment experienced local OBE and SSE exceedences recorded by the passive sensors located at the HPCI room sub-basement.

The measured and artificial response spectra compare favorably. The artificial response spectra for the east/west direction very nearly matches the measured response spectra, while the artificial response spectra for the vertical direction essentially envelopes the measured response. The data point at 4 cps falls outside the artificial response spectra, and may be attributed to the rumbling felt throughout the buildings.



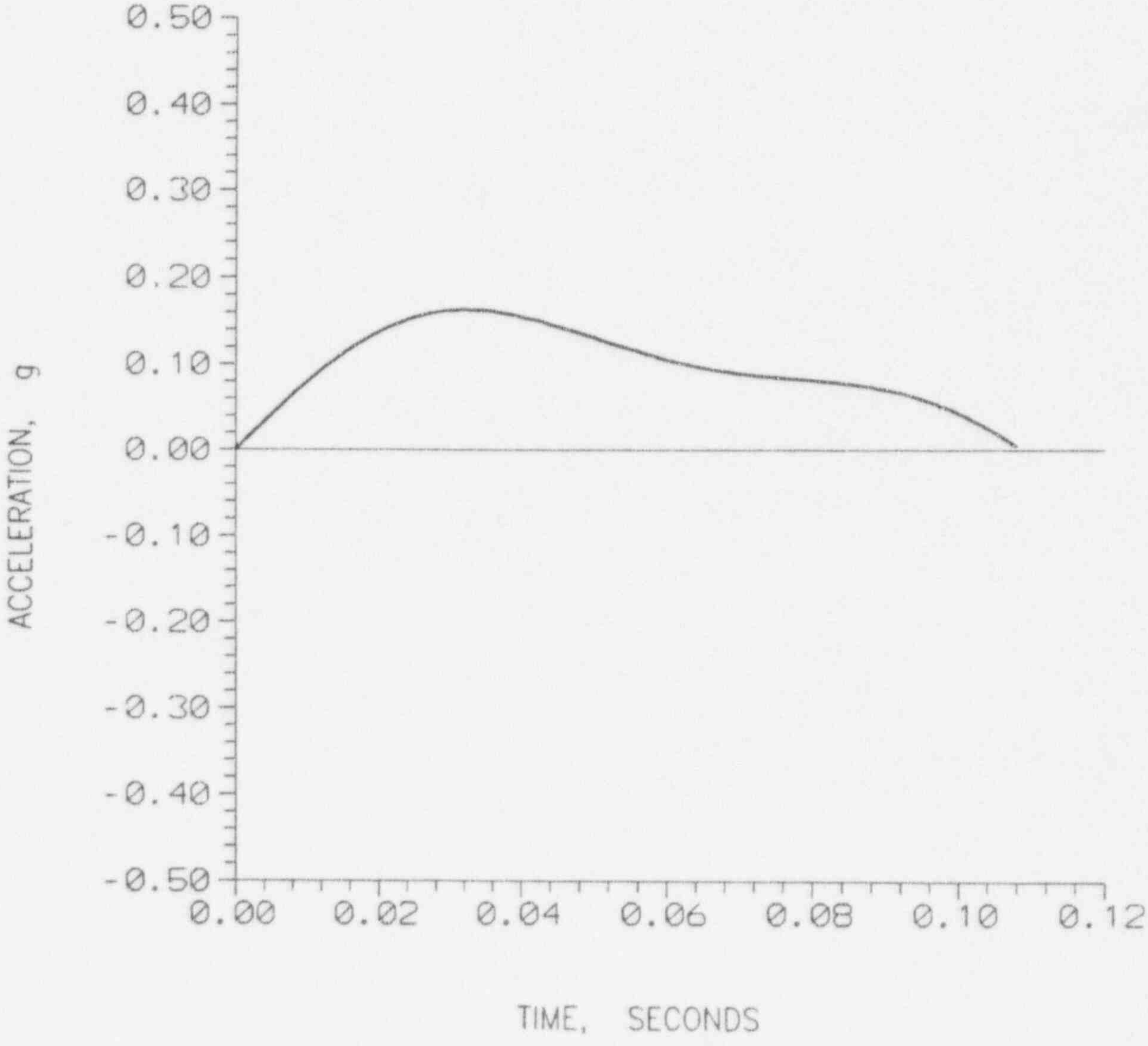
Artificially Generated Time-History, East/West Direction - HPCI Room

Figure 3.2.2.1



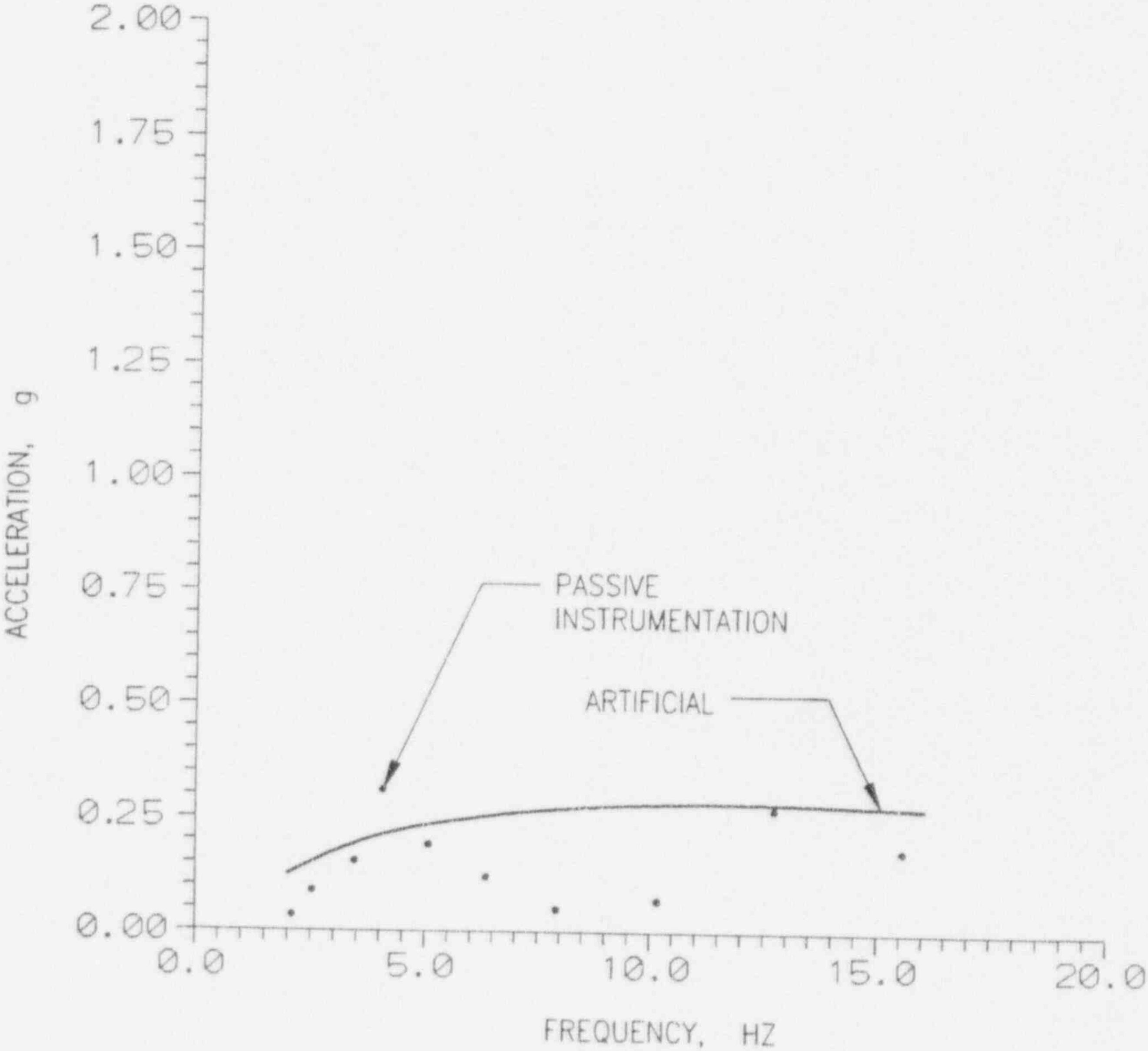
Artificial Response Spectra for East/West Direction - HPCI Room

Figure 3.2.2.2



Artificially Generated Time-History, Vertical Direction - HPCI Room

Figure 3.2.2.3



Artificial Response Spectra for Vertical Direction - HPCI Room

Figure 3.2.2.4

The artificial time-histories are similar to shock incident time-histories, as evidenced by tne short duration and high accelerations. The time-histories, in conjunction with the event observations, research, and subsequent walkdowns, suggest the turbine failure event was an impulse type shock incident with low energy and short duration, unlike an earthquake which imparts high energy into the structures and is of relatively long duration.

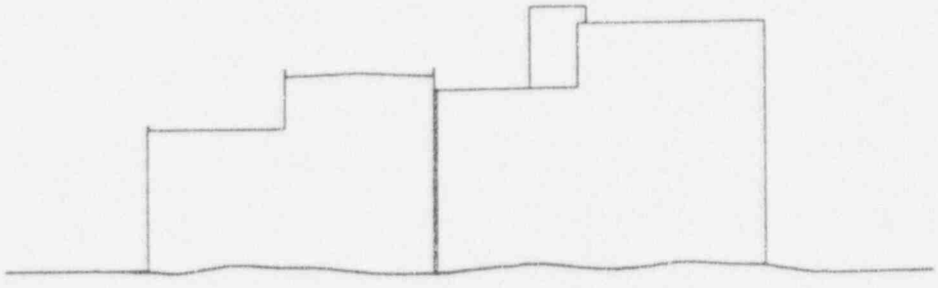
All equipment in the Reactor/Auxiliary building functioned as expected during the turbine failure and reactor shutdown. An inspection, after the event, of Reactor/Auxiliary Building areas which are adjacent to the Turbine Building produced no indications of structural damage. Furthermore, the extant safe shutdown equipment adequacy was proven by the satisfactory safe shutdown experience.

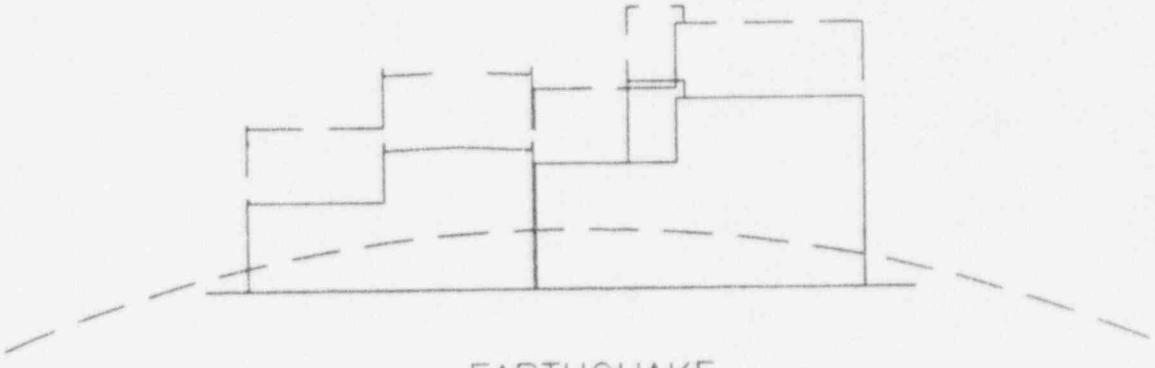
4.0 CONCLUSION

The turbine failure at Fermi 2 on December 25, 1993, should not be compared with a tectonic earthquake, and globally, the Reactor/Auxiliary building did not experience OBE excitation levels. The turbine failure was a shock incident, resulting in dynamic response phenomena of a wave propagating through the building foundation without exciting the structure above.

An earthquake imparts long duration, broad range frequencies, and high energy into a structure, while a shock impulse imparts short duration, high amplitude, and low energy into a structure. Industry standards recognize shock impulses do not cause significant structural distress.

The ratio of the shock wave length resulting from the turbine event at Fermi 2 and the building length is much less than the corresponding ratio of an earthquake wave length and the building wave length (Figure 4.0.1). While the shock incident produced local high accelerations, the short duration, low energy, and small deformations associated with these high frequency accelerations did not compromise the structural integrity of the Reactor/Auxiliary building or the equipment therein.





Schematic Representation of Impulse Tremor Versus

Earthquake Wave - Vertical Direction

Figure 4.0.1

5.0 REFERENCES

1) Detroit Edison Company, Enrico Fermi 2; Updated Final Safety Analysis Report.

2) Hasrouni/Hopper; Detroit Edison, Enrico Fermi 2 Site Visit - Fermi 2 Turbine Failure - Post Event Earthquake Evaluation; January 11, 1994.

3) Detroit Edison Company; Technical and Engineering Services Report 94R71-1; Analysis of DVA Vibration Alarm/Coastdown Magnetic Tape for Fermi 2 MTG; January 11, 1994.

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5) Detroit Edison Company; Written Observations from Fermi 2 Personnel; December 25, 1993.

6) The Cleveland Electric Illuminating Company; Seismic Event Evaluation Report; Perry Nuclear Power Plant Docket Nos. 50-440, 50-441; February 1986.

7) Letter from K.E. Howard to David Hopper TMPE-94-0389 File 0801.21, Fermi 2 Turbine Failure - Post Event Earthquake Instrumentation Data Evaluation; June 27, 1994.

8) Landa/Schell; Detroit Edison, Enrico Fermi 2 Site Visit - Fermi 2 Turbine Failure - Post Event Evaluation; March 6, 1994.

9) Hopper/Hasrouni; Detroit Edison, Enrico Fermi 2 Site Visit - Fermi 2 Turbine Failure - Post Event Evaluation; April 21 and April 26, 1994.

10) Todorovska, M.I. and Trifunac, M.D., "Note on Excitation of Long Structures by Ground Waves", Journal of Engineering Mechanics, Volume 116 #4, April 1990.

ATTACHMENT 6