IN SITU TESTING FOR SEISMIC EVALUATION OF HUMBOLDT BAY NUCLEAR POWER PLANT OF PACIFIC GAS AND ELECTRIC COMPANY

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I. INTRODUCTION

A. The Need for Seismic Reevaluation. In response to a Nuclear Regulatory Commission (NRC) request, it was required that the seismic design of safety related structures, systems, and components at the Pacific Gas and Electric Company Humboldt Bay Power Plant Unit 3 be evaluated using present day methods of seismic analysis.

The Unit 3 plant is an operating plant powered by a Boiling Water Reactor. The plant was designed during the period 1959-1961. Those parts of the plant related to nuclear safety were designed to withstand a seismic load of 0.25 times the dead load and equipment load, or 0.20 times the dead load plus one half the live load, whichever was greater. The seismic load factor used in the original design was based on seismological studies and exceeded the seismic load factor of 0.133 g prescribed by the Uniform Building Code in effect at that time.

In the time since the original design, significant changes have occurred in the methods of seismic analysis of nuclear power plants. Specifically, dynamic analysis methods are now used for all safety related structures, systems, and components, with structural amplification being included in defining input motions for equipment and piping located in structures. Additionally, allowable stresses have changed and alternative acceptance criteria are now used in certain instances. Also, more detailed seismological investigations have been conducted at the plant site and greater seismic design input has been defined.

Evaluation of the seismic design of the plant and design of certain modifications has been completed to provide the additional margin of safety required by present day methods of seismic analysis. This report describes how in situ vibratory testing was performed and how test results were used in the plant evaluation and in the design of plant modifications.

B. New Seismic Criteria. The objective of the seismic design evaluation was to determine whether safety related portions of the plant could withstand a 0.25 g operating basis earthquake (OBE). Where modifications were found necessary to withstand the OBE, the modifications were also designed for a 0.50 g Safe Shutdown Earthquake (SSE). Seismic evaluation was accomplished by analysis, by testing, by comparison of plant components with similar qualified items, or by a combination of these methods.

Seismic analyses were performed utilizing dynamic analysis methods in which the seismic input, defined by NRC response spectra, was applied to analytical models to determine seismic forces for use in stress analyses or to determine structural amplifications and amplified response spectra for use in the seismic analysis of equipment and piping located in the structures.

The new criteria required that seismic analysis consider the effects of concurrent input motion in two horizontal directions and the vertical direction.

C. The Need for In-Situ Testing. In the evaluation of the complex structures, systems, and components making up the existing and operating Humboldt Bay Unit 3 Nuclear Plant, analytical methods, although generally sufficient, were of limited use in certain instances. Analysis alone, of some complex systems, was found to be impracticable, costly, require excessive time, or, in the case of critical items, warranted verification by testing. In some cases, excessive efforts would have been required to obtain as-built construction details necessary for performance of analyses. Off-site laboratory testing to proof test components or to determine dynamic behavior was not feasible where components could not be physically removed, when removal could have disrupted plant operation, or where removal and transporting to a remote location could have entailed unacceptable risk of damage to components which could not have been replaced or repaired in a reasonable time. In these instances, in-situ testing provided an effective means of supplementing theoretical analysis and laboratory tests.

Testing was used often to determine dynamic properties for use in preparing or verifying analytical models. Test data included resonant frequencies, mode shapes, and damping. Use of test data to provide estimates of damping was limited as, due to practical or safety limitations, components could generally not be excited to high levels of response at which higher damping corresponding to that expected to occur during the design earthquakes would be present. Resonant frequencies determined by testing were used to verify analytical models. Where the resonant frequencies of the model agreed fairly closely with those measured on the actual structure, there was greater confidence in the model and modeling method. On the other hand, where the frequencies did not agree, or the test was performed prior to actual modeling, the test data was used to suggest how to improve the model, or to help establish a modeling approach, or to choose between several candidate models. On a very simple level, items such as motors or pumps were by a quick test, shown to be rigid, having no resonant frequencies below 33 Hz, thus justifying quasi-static analysis.

In some cases more extensive testing was performed in which resonant frequencies, mode shapes, and accelerations were measured; this permitted models of complex structures to be created from experimental data alone.* These models were suitable to predict seismic acceleration and displacement response, but were not suitable to predict detailed stresses or strains. This approach was useful where a structure was modeled only to provide input to another component, such as modeling or an electrical enclosure to determine input to instrumentation mounted in the enclosure.

A limited amount of proof testing can be performed in-situ, although increasingly strict regulatory proof test requirements and practical or safety limitations are virtually eliminating these possibilities. In-situ "proof" tests were used generally to roughly quantify seismic capacities of some items and to flag problem areas.

In general, the in-situ testing was used to point out problem areas, speed up theoretical analysis, and to provide greater confidence for both the analyst and the regulatory body in the seismic evaluation. In-situ testing was a useful supplement to theoretical analysis, off-site testing, and in some areas provided information not predictable by theoretical means. Availability of data enabled

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*Ibáñez, Paul, "Review of Analytical and Experimental Techniques for Improving Structural Dynamics Models," Pressure Vessel Research Committee, Welding Research Council, (January 1977).

analytical conservatism to be reduced and was of significant benefit in requalifying this older plant to new and more stringent regulations.

D. Tabulation of Tested Equipment. In all, some four dozen different equipment, piping, and structure items were tested to identify their frequencies of vibration in one or more principal directions, to estimate damping ratios in their lower modes, and in some cases to map the shapes of their lower modes. Most pieces of equipment tested were either essential to the safe operation of the plant or its failure due to seismic loading could possibly inhibit safe operation.

The equipment tested is categorized into five major groups: tanks and similar devices, pumps and motors, electrical cabinet and instrumentation, piping and valves, and major structures. Table I presents a detailed summary of tested equipment along with methods used to excite these structures.

II. DISCUSSION OF EXPERIMENTAL METHODS

A. Coordination of Testing and Analysis. Prior to start of the test operation, it was essential to study all the safety-related systems to determine the complexity of the analytical model, extent of the analysis that had to be performed, availability of the detailed drawings showing the support and the structural details, and the extent of the results required to be obtained from the insitu testing.

B. Testing Methods. The vibration tests carried out used a variety of excitation, sensing and recording methods. Eccentric mass vibrators were used to provide steady-state sinusoidal input to structures. Using these vibrators, the properties of which are shown in Table II, we were able to determine resonant frequencies, damping and mode shapes. The latter were determined by forcing near the resonant frequency, placing accelerometers at several locations on the structure and comparing the measured response with a reference response. Resonant frequencies were identified by the peak in response as the forcing frequency was slowly changed. Bandwidth of the peaks yielded an estimate of damping. These vibrators allow identification of structures as small as electrical instruments and as large as entire containment buildings.

Structures were also excited by transient forces--ambient, impact, and snapback. Often ambient response was dominated by the operating speeds of nearby rotating machinery and yielded little useful information. Impact tests were carried out by striking the structure with a rubber mallet, one's hand or body or other objects. Snapback testing was performed by pulling the structure with a cable or pushing it with a hydraulic ram and suddenly releasing it. The resulting transient decay could then be analyzed to identify dynamic properties. Recent improvements in data analysis include the use of FM tape recorders and digital data analysis. Other instruments include filters, single and double integrators, phase measuring devices, and adding amplifiers used to add or subtract signals so as to enhance a particular mode of vibration. Figure 1 illustrates a typical instrumentation system.

The dynamic response of the structures was measured using a variety of accelerometers, covering the range from 10^{-5} to 10^2 g. The accelerometers which had flat response from DC to 100 Hz were connected to multichannel strip chart recorders, single and dual integrators and a spectrum analyzer. Transducers were connected to instrumentation by cables that were quickly installed and removed over several hundred feet distances. No interference with normal plant operation was required. The strip charts and the X-Y plots available from the spectrum analyzer provided permanent records of the test data along with the test log sheets. The spectrum analyzer, a Spectral Dynamics Model 330, is capable of full-scale frequency ranges from 2.5 Hz to 20,000 Hz, with resolution 1/250 of full scale. The spectrum of a transient acceleration trace is essentially the modulus of the Fourier transform and as such has the units of velocity. For steady-state sinusoidal response, however, the amplitude is most conveniently related to acceleration. In any case, the location, relative magnitude and width of resonant peaks are much more significant than their actual magnitude. The spectrum analyzer can be operated in moving average, time average or peak hold modes. From the spectra, the resonant peaks in the response are easily identified. When performing tests, it is common to analyze the unforced, ambient, signal first and then the forced response in order to distinguish between external coherent input and actual resonant peaks in the response.

Note that the methods of excitation do not attempt to simulate an earthquake. The object of the testing is to excite, by any means, the same modes of vibration that are important to the earthquake response. Techniques have been developed and proven out by experience to accomplish this. Also, while tests on major structures such as buildings often yield suspect data due to nonlinearities in soil-structure interaction, equipment can often be excited to a sufficiently high level to adequately define the properties important to earthquake response. The errors due to nonlinearities in the experimentally-determined parameters are then less than the errors due to nonlinearities in theoretically-determined properties.

III. CASE STUDIES

The five case studies discussed below are typical of those in which the experimental and theoretical analysis were closely integrated. The physical description of the structure, the need for testing, test results, and use of these results in qualification analysis or design modifications are presented. The five case studies are a liquid poison tank, an emergency generator, the reactor control board, the ventilation stack, and the control room floor.

A. Liquid Poison Tank. For the poison tank, test data were used to simplify analysis of the existing tank. Properties determined by testing were used in improving the analytical models used to evaluate the tank and to design modifications.

Snapback techniques were used to determine damping ratios and eigenfrequencies of the poison tank (Figure 3) in two principal horizontal directions. In addition, the poison tank effluent pipe and neighboring valves were impact-tested to determine their resonance frequencies. The poison tank is a vertically-mounted cylindrical tank founded on three steel angle legs. It is approximately 12 feet high, 4½ feet in diameter, and is made of steel.

Prior to snapback testing of the poison tank, low order modes of the effluent pipe and its neighboring valve were identified at 21.2 Hz, 12.4 Hz, and 9.2 Hz. Snapback testing was achieved by tightening a 3/16" diameter wire rope between the top of the poison tank and a distant fixed point. Approximately 2000 Newtons (500 lb) force was applied in the east-west direction. The wire rope was then cut instantaneously. Two resonant frequencies were identified using a spectral analyzer: one at 6.5 Hz and one at 30 Hz. Damping at the lower first model frequency was not determined. The second mode at 30.0 Hz had damping of 2.0 percent critical. North-south snapback testing indicated the north-south eigenfrequencies at 6.0 Hz and 26.1 Hz with damping of 4.6 percent in the 26.1 Hz mode. Peak accelerations achieved were slightly greater than 1.0 g.

Test frequencies were helpful in indicating the interaction at the junction of the vertical support steel angles and the tank shell and its influence on the vibratory characteristics of the tank model. A lump mass model of the tank was prepared initially with rigid links connecting the vertical cantilever model of the tank to the three steel angles. The frequencies of the tank thus obtained were higher than the test frequencies. Subsequently, a finite element analysis of the junction area of the support angles and the tank shell was performed to determine the spring stiffnesses of the rigid link in the model. These spring stiffnesses for the links were used in the final analysis and the design of the modifications of the tank, which gave much closer correlations between the test and analytical frequencies.

B. Emergency Generator. High-level in situ testing during which the generator performed its required function was used directly to demonstrate the seismic capability of the generator. The emergency generator (Figure 3) is a 60 kW, propane-fueled, engine-driven generator mounted on a concrete foundation at grade. The engine is mounted on a supporting steel frame by means of a triangular array of rubber mount pads. This type of engine mounting is common to the auto industry with two mounts at the rear corners of the engine to transmit torque and one mount at the front center of the engine to transmit thrust. These mount pads complicated testing considerably by allowing rigid body translation and rocking in a highly-nonlinear manner. The assembly is surrounded by a sheet metal cover. There is an instrumentation and control panel mounted on the interior of the cover assembly at the south end.

Testing proceeded in two phases. Phase 1 was a series of tests designed to identify resonant frequencies, damping values and mode shapes in the north-south, east-west, and vertical directions. Since the mounts introduced significant nonlinearities, several sweeps were made in both directions at varying force levels to determine the dependence of these parameters on force level. In the north-south direction (axial), first mode resonance occurred at 11.75 Hz with the shaker set at 10 percent of full force and 12.50 Hz with the shaker set at 50 percent.* Damping went from 10.7 percent at 10 percent full force to 7.6 percent at 50 percent full force, probably due to saturation of the highly damped rubber supports.

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*The force at 100 percent is given by 4.6 f^2 lbf where f is the frequency of excitation.

A second resonant peak was found at 16 Hz; no damping ratios were determined for this frequency. The mode shapes were determined. Both are rigid body translation with rocking, the only difference being the location of the rotational axis and relative phase of response.

In the east-west direction (transverse), resonance peaks were found at 5.60 Hz and 9.80 Hz when the shaker was set at 30 percent full force and at 4.50 Hz and 9.70 Hz when the shaker was set at 100 percent full force. Both mode shapes are rocking; the only difference again is the location of the rotational axis. Accelerations achieved in both north-south and east-west directions ranged between 0.3 and 1.0 g. The lowest sheet metal cover mode was found at 18 Hz.

Phase 2 was a sequence of tests designed to achieve high level response in the emergency generator and its control panel. To include the control panel in the test, it was removed from the sheet metal cover and strapped to the rear of the generator. Since the vertical component of the rigid body translation and rocking in both directions is a maximum at this point, the control panel was subjected to as much if not more input motion than the generator itself. Since estimates of damping ranged from 10.7 percent to 7.6 percent, a conservative estimate of 5.0 percent was assumed. For this value of damping, in the range of 9 Hz, an acceleration amplification factor of 2.61 was defined by the design earthquake spectra. To perform a high-level test on the emergency generator, the MK-12 vibrator was set at a force level to supply at least 1.31 g biaxial excitation, corresponding to an SSE input of 0.5 g amplified by a factor of 2.61, at each resonance frequency and maintain that level of excitation for a reasonable time during which the generator was to be brought from standby condition to operating with load condition and back to standby condition. This indeed was done while control and power supply functions were monitored, with no adverse conditions noted. Table II summarizes the test sequence. All accelerations were recorded at approximately the center of mass of the system.

Since an east-west response of at least 1.31 g was not attainable through forced vibration testing in the 4.60 mode, it was decided to check the mounts for this mode by static displacement.

A hydraulic actuator was positioned between an adjacent wall and the approximate center of mass of the emergency generator. Approximately 7700 lbs of force was applied, at an angle a few degrees off horizontal, to attain a displacement slightly greater than 0.6 inch. No adverse effects were noted.

Tests performed to identify the flexing modes of the motor/generator system itself indicated no resonant frequencies below 25 Hz.

In order to account for differences between the test excitations and those defined for the design earthquakes, including consideration of concurrent multidirectional excitation, accelerations observed during testing were reduced and compared to required response spectra. Although the equivalent accelerations did not equal the required response spectra at all frequencies, they were sufficiently high to indicate adequate seismic capability of the emergency generator.

C. Reactor Control Board. Testing gave early demonstration of high amplifications at the north face of the Reactor Control Board (RCB). Test data were used to simplify analysis and to obtain properties which could not practicably be determined by analysis. Properties determined by testing were used to analyze the existing panel structure, to design modifications, and to determine response spectra for subsequent off-site vibratory testing of devices mounted in the panel.

The RCB, shown in the background of Figure 4, is a steel panel and steel braced electrical cabinet consisting of three sections each of which support instruments at the north and south sides of the cabinet. There are doors on the east and west ends of the cabinet which provide access to the inside of the cabinet. The extreme west section is a separately fabricated unit of slightly different cross-section from the middle and east sections and is connected to the middle section. The cabinet' is bolted to the concrete operating room floor.

The MK-10 vibrator was used to sweep up to 30 Hz while measuring north-south and east-west response of the RCB. These data identify the modes affecting the main structural system. Significant resonant peaks were seen at 7.18 Hz, 8.00 Hz, 10.1 Hz, 11.8 Hz, 14.00 Hz, 17.5 Hz, 19.2 Hz, and 22.5 Hz. Figure 5 presents a typical response shape while forcing at 8.00 Hz, which is dominant north-south motion of the entire RCB. The 7.18 Hz mode is a localized effect involving mainly the counting equipment on the NE panel. The 10.1 Hz mode is dominantly the motion of the SE panel. The 11.8 Hz mode involves large motion of the SW, NW, and NE panels. The remaining modes are a complex combination of individual panel and main structure motion.

A series of tests were performed to determine the individual resonant frequencies and mode shapes of each panel of the RCB. The NE panel, for example, responds at "cabinet" modes near 7.18, 10.1, and 19.2 Hz and also at its own 13.2 Hz mode (2.0 % damping). At the cabinet modes, the panel follows the cabinet with some bowing at its center. This mode is associated with the EW and NS motion of the heavy counting device flexing on the panel wall.

Similar results were found on the other six panels with fundamental modes varying between 11.3 Hz and 17.1 Hz with damping of 4.0% to 10.0%.

Yet another series of tests were conducted on sixteen selected instruments in the RCB. The instruments were man-excited and monitored triaxially. The intent of these tests was to see if the instruments possessed localized modes not associated with the cabinet or panels. Note that this test was *not* designed to identify the modes of small internal components inside of the instruments but rather modes having dominant motion of the casing or support structure of the entire instrument.

Many resonant frequencies were noted in the response of the instruments. Most, however, were the cabinet or panel modes, or above 25 Hz. Very few instruments possessed their "own" modes of vibration. One instrument has a low frequency mode due to a flexible appendage. Two other instruments had modes below 25 Hz (at 14.6 and 17.3 Hz), one parallel and one perpendicular to the panel wall. All other instruments were only affected by panel and cabinet modes.

In summary, the RCB has modes of vibration associated dominantly with the motion of the entire cabinet and modes associated dominantly with each panel. No significant vertical modes were found. The panel modes, all with dominantly NS motion range from 10 to 20 Hz and involve panel bowing or opposite motion of the top and bottom or east and west of the panel. Damping for the panel modes varied from 2% to 10%. Tests on various instruments indicated that most follow the motion of the cabinet and panel without input modification. A few instruments, with flexible appendages magnify input motions. A few instruments had additional resnances in the 10-20 Hz range.

The frequencies of vibration and mode shape values obtained from the *in situ* testing were used together with the calculated masses at the selected node points in the subsequent analysis to check stresses in the reactor control board structural members as well as support connections. The response time histories of accelerations and acceleration response spectra of these time histories were also generated analytically at the locations where the safety-related electrical instruments were mounted. These spectra were subsequently used in the off-site vibration testing of these instruments.

As mentioned earlier, the reactor control board is comprised of three bays or segments with steel framing angles on sides of each bay. The response spectra were analytically generated using the test data at the node points on the steel framing as well as on the steel plate panels between the frames. The spectra at the node locations on the steel panels where the electrical instruments are located showed very high amplification compared to the spectra on the steel framing. This indicated a need for stiffening of the steel panels. The panels were stiffened by providing horizontal steel flat bars across the panels such that the funamental frequency of vibration of the panel would be higher than 33 cps.

D. Ventilation Stack. Properties determined by testing were used to verify analysis of the ventilation stack. Several tests were concerned with ambient and snapback testing of the Unit 3 stack (Figure 6). The reinforced concrete stack, 250 ft high, located just north of the reactor refueling building and caisson is founded on a reinforced concrete base integral with the 60 ft diameter reactor caisson which is embedded 70 ft below grade. The stack tapers from 18 ft diameter at the base to 5 ft at the top. Shell thickness varies from 10 in. at the base to 6 in. at the top.

Transducers were placed on the stack at midpoint and top elevation. Figure 7 shows the spectral response from ambient vibrations less than 10^{-3} g due to, among other sources, an 8 mph wind. A first mode at 0.57 Hz and a second mode at 2.04 Hz are apparent. Undoubtedly the first mode is actually a double mode, one for each principal direction. In the first mode the top of the stack is moving three times as much as the mid point. Data at a higher frequency range indicate that the third mode is split (4.75 and 5.03 Hz), but only by 6 percent, reflecting the symmetry of the stack. The fourth mode is at 8.44 Hz. The data also indicate additional modes at 13.20, 14.75, 18.40, 19.20, and 24.1 Hz. These data are summarized in Table III along with the results of the snapback tests and theoretical models, to be discussed shortly.

The ambient response came from accelerations on the order of 10^{-3} g or less. To obtain data from responses at higher levels a 1/2 in. steel cable was strung between the 125 ft elevation (mid point) of the stack and the 95 ft elevation (roof) of the Unit 2 boiler structure. The cable was pretensioned to approximately 300 lbs. Then a side pull with a second cable was used to tension the main cable to 17,000 lbs. The second cable was then cut with a large bolt cutter resulting in a snapback excitation. The snapback produced excitations 10 to 20 times as great as the ambient. Frequencies decreased slightly from the ambient values as summarized in Table III. The second mode damping, as determined by the half-power-bandwidth method, is 5.0% (for peak accelerations of 0.03 g). The damping for the first mode is best found from the temporal response, Figure 8, by the logarithmic decrement method. These data, from first mode peak acceleration of 0.005 g at mid stack, indicate 10% damping.

A fixed base, lumped mass beam mathematical model of the stack was utilized in the seismic analysis. The analysis showed the stack to be capable of resisting both the OBE and the SSE within allowable stress limits. Frequencies of the mathematical model were calculated and found to compare closely to observed frequencies, as shown in Table III. The calculated frequencies were determined considering concrete effective in resisting tensile stresses considered not to exceed the modulus of rupture. These frequencies correspond to a condition of low excitation similar to that imposed during testing of the stack.

During conditions of high excitation similar to the OBE and SSE conditions, tensile stresses will exceed the modulus of rupture of the concrete, resulting in a cracked section condition in which tensile forces are resisted by the reinforcing steel. Under these circumstances the effective moments of inertia will be significantly less than that of the gross concrete cross sections, resulting in lower frequencies of the stack. As predominant modes of the stack are in the frequency range of the design response spectra where response decreases with decreasing frequencies, seismic response of the stack will be less severe as the extent of the cracked section condition increases along the height of the stack. Thus seismic response of the stack is dependent upon the extent of the cracked section condition along the height of the stack. In the OBE and SSE analysis of the stack the extent of the cracked section condition was determined and seismic forces calculated were shown to be in reasonable agreement with those required to produce the extent of cracking determined.

E. Control Room Floor. Testing gave early demonstration of the potential need for stiffening the Control Room Floor in the vertical direction. Properties determined by testing were used to verify analysis of the existing floor system and aid in the design of modifications.

These tests investigated the control room floor vertical response. The concrete floor is supported by steel beams and columns and by walls in contact with or shared with other structures on the north, east, and west sides of the room. As the vertical response of the floor will effect the input to category A instrumentation, the vertical response of the floor due to vertical forcing was investigated. The MK-12 vibrator was weighted down with 300 lbs of steel plate in order to remain stable while exciting the floor.

The response at a typical location is shown in Figure 9. The fundamental vertical mode occurs at 9.8 Hz with 10 percent damping at 0.01 g accelerations. There are several other modes at higher frequencies: 13 Hz, 16 Hz, 22, Hz, and 25 Hz. The mode shape of the 9.8 Hz mode is presented in Figure 10, and as anticipated indicates vertical bowing of the floor.

The Control Room floor slab and steel beam framing system were modeled as finite elements representing concrete slab and three dimensional beam elements representing steel beams. Dynamic analysis was performed to calculate frequencies and mode shapes of the floor system without modifications in the vertical direction. The analytical frequencies compared very well with the test frequencies indicating that the model was adequate. The floor was then vertically stiffened by providing vertical steel columns at midspan of several beams and girders. The fundamental frequency of the floor in the vertical direction was increased from 10 Hz to Hz after modifications. The vertical response spectra were analytically generated at the locations where the electrical cabinets were supported which were subsequently used in the analysis and design of the cabinet structures and in the off-site vibration testing of the safety related electrical instruments.

IV. CONCLUSIONS AND INFERENCES

At the Humboldt Bay Plant the use of *in situ* testing proved to be a rapid and economical means of obtaining a wealth of data that was primarily useful in giving direction to, speeding up, and giving confidence to analyses that were required to be performed for the seismic evaluation. The direct effort required for the testing of 44 structures or components, including preparation of a summary report, was about 3,000 manhours. All of the testing was performed during an initial 40 day period and a follow-up period of 6 days. Testing was performed up to 18 hours per day with minimal disruption of plant activities. All test data obtained was available for use within 30 days after completion of tests. In many cases, data was available for use immediately upon completion of testing. At the time of testing, classification of nuclear safety related structures, equipment and systems had not been completed, so that scope of the seismic evaluation was not firm. Items selected for testing were those considered at the time to have the greatest potential for being classified as nuclear safety related. As a result of this lack of definition, some test data obtained has not, at this time, been used. Even so, for those items where test data was utilized, testing has been cost effective.

Testing was most useful in obtaining data to facilitate analysis of storage tanks, pumps and motors, and electrical panel enclosures. Data obtained regarding behavior of piping and valves were generally not used as detailed analyses utilizing standard piping analysis methods were generally required. Testing of building structures was useful primarily to provide more confidence in analytical models and to identify problem areas.

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TABLE I

SUMMARY OF EQUIPMENT TESTED

Item	Purpose				Method				
	Resonant Frequency	Damping	High Level Tests	Mode Shapes	Ambient	Sinusoidal	Snapback	Impact	Static Displacement
Storage Tanks & Similar Devices									
Fresh Water Storage Tank	x	x			x	x	x		
Diesel Fuel Storage Tank	x				x			x	
Liquid Propane Storage Tank	x	x					x	x	
Gas Scrubber Recirculation Tank	x				x			x	
Scram Dump Tank	x	x			x			x	
Gas Scrubber Column	x	x			x			x	
Suppression Chamber Cooler	x	x	x	x	x	x		x	
Poison Tank & Associated Valves	x	x			x		x	x	
Emergency Condenser	x	x		x	x	x			
Condensate Storage Tank	x	x	x					x	
Unit II Deaerator	x	x			x		x	x	
Pumps & Motors									
Auto Diesel Fire Pump #2	x				x			x	
Emergency Generator	x	x	x	x	x	x	x	x	x
Core Spray Pump	x				x			x	
Clean-up Pump	x	x						x	
Rotary Inverter	x				x			x	
Electrical Cabinets & Instrumentation									
Auto Diesel Fire Pump Relay Stand	x	x	x		x		x	x	
Motor Control Center 10	x	x		x	x	x		x	
Emergency Lighting Panel 364	x	x	x					x	
Motor Control Center 11	x	x		x	x	x		x	
Valve Control Center #1	x	x		x	x	x		x	
Reactor Control Console	x				x			x	
Turbine Generator Board	x	x		x	x	x		x	
Heating & Ventilation Control Board	x	x		x	x	x		x	
Reactor Control Boards									
Scram Rod Hydraulic Control Manifold	x	x			x			x	
Reactor Control Panel	x	x			x			x	
West Accumulator Control Panel	x	x			x			x	
Piping and Valves									
D.C.&A.C. Recirculation Pumps and Piping	x				x		x	x	
Accumulators - West Bank	x	x	x		x		x	x	
Accumulators - East Bank	x	x	x		x		x	x	
Solonoid Valves near SRHC	x	x						x	
Hydraulic Selector Valves	x							x	
Main Steam Line	x	x						x	
Cable Tray 3DE02	x	x						x	
CV 4357, Air to Gas Scrubber Column	x	x						x	
CV 4186, Hydraulic Return	x	x						x	
Major Structures	x	x	x	x	x	x	x	x	x
Fire Pump House	x					x			
Refueling Building	x	x		x		x			
Stack	x				x		x		
Unit II Boiler Structure	x	x		x	x	x			
Control Room Floor	x	x		x	x	x			
Turbine Pedestal	x	x		x		x			
Turbine Auxiliary Building	x			x		x			

TABLE II

STRUCTURAL VIBRATORS DESIGNED AND USED BY APPLIED NUCLEONICS COMPANY

Type	Weight lbs	Maximum Force Output (lbf)	Maximum Eccentric Moment Kg·m	Frequency Range (Hz)
MK 10	2.2	40	7.04×10^{-3}	1.0-80
MK 11	25	10,000	0.113	0.5-100
MK 12	150	10,000	0.52	0.5-100
MK 13	350	10,000	10.2	0.5-20
MK 14	800	10,000	352	0.1-9.0

TABLE III

STACK RESONANT FREQUENCIES (Hz)

Mode #	Ambient Measured 10^{-3} g	Snapback Measured 10^{-2} g	Low Excitation Model	OBE/SE Model
1	0.57	0.55		
2	2.04	1.99		
3	4.75, 5.08	4.65		
4	8.58	8.44		
5	13.2	-		
6	14.8	-		
7	18.4, 19.2	-		
8	24.1	-		

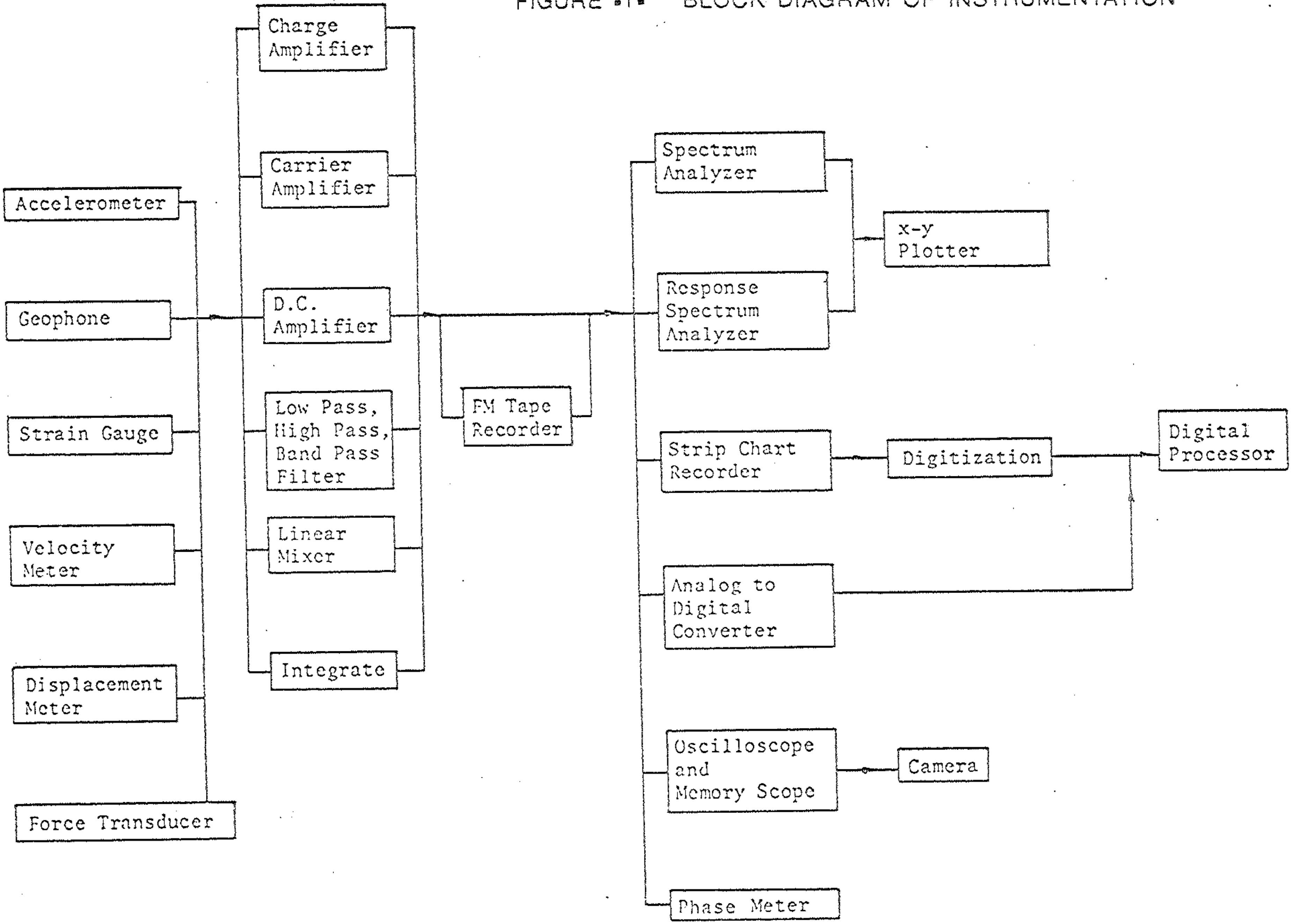
TABLE IV

EMERGENCY GENERATOR HIGH LEVEL TEST SEQUENCE

Frequency (Hz)	Direction of Excitation	% Full Score	Horizontal Acc. (g)	Vertical Acc. (g)
9.5	N-S, 45° off horizontal	100	1.82	2.0
15.5	N-S, 45° off horizontal	50	2.01	2.3
4.6	E-W, 45° off horizontal	100	0.60	0.6
8.9	E-W, 45° off horizontal	100	1.40	1.5

In all cases the duration of excitation was greater than 60 seconds during which the generator was started, operated, and shut down repeatedly.

FIGURE 1. BLOCK DIAGRAM OF INSTRUMENTATION



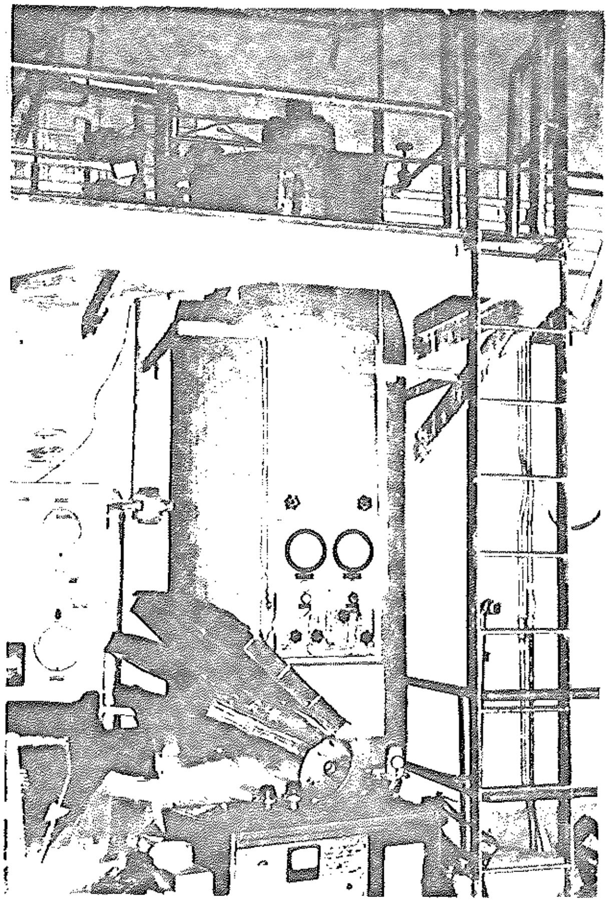


FIGURE 2: LIQUID POISON TANK

FIGURE 3: EMERGENCY GENERATOR

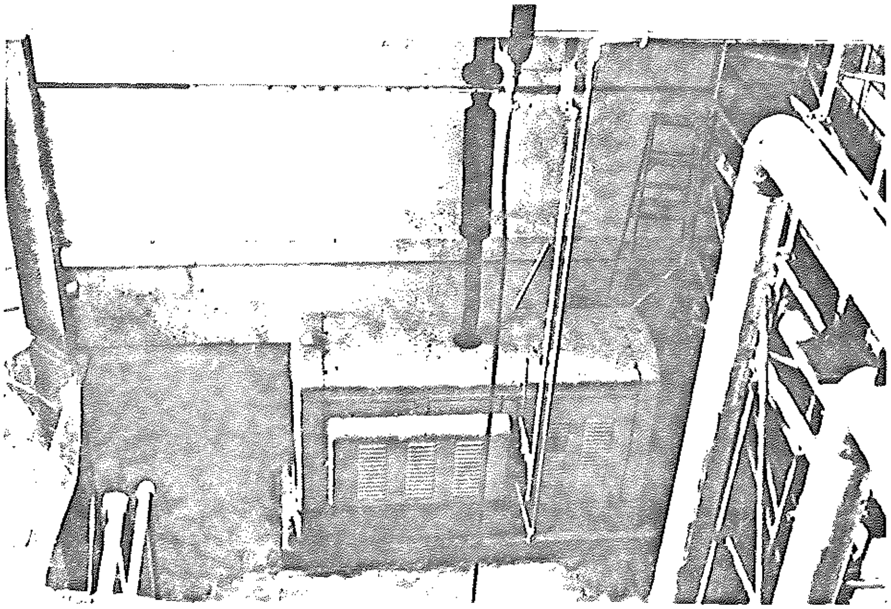
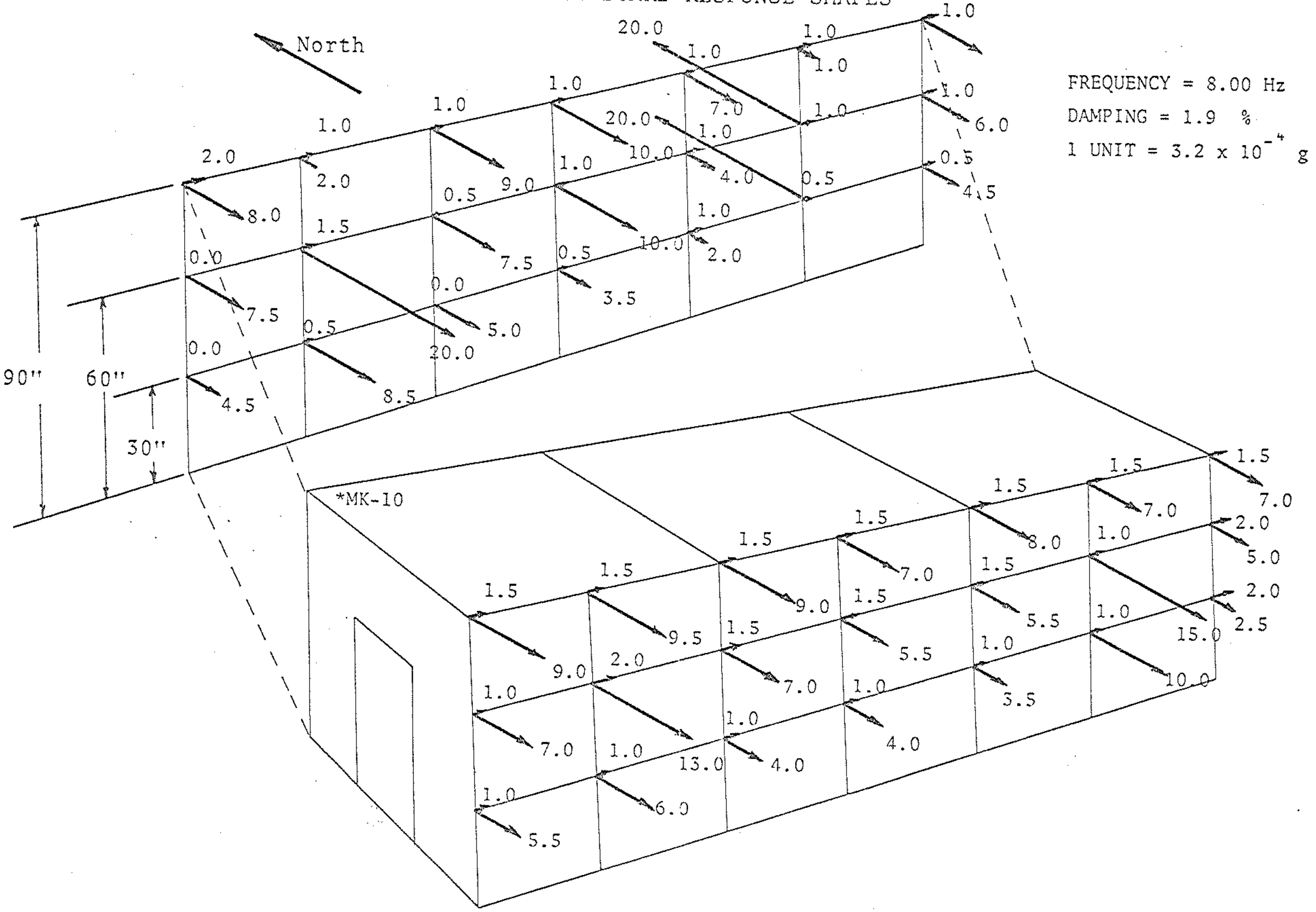


FIGURE 5
REACTOR CONTROL BOARD RESPONSE SHAPES



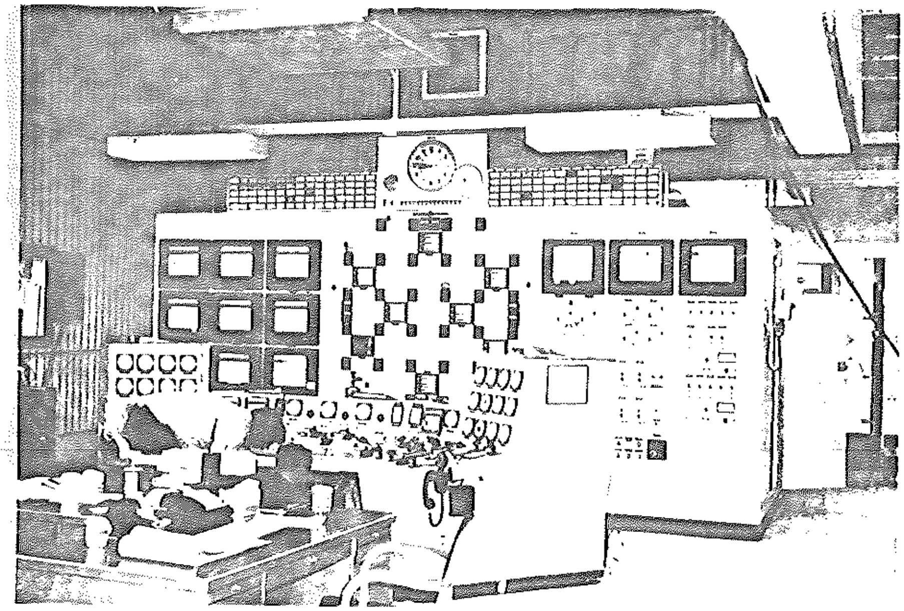


FIGURE 4: REACTOR CONTROL BOARD (In Background)

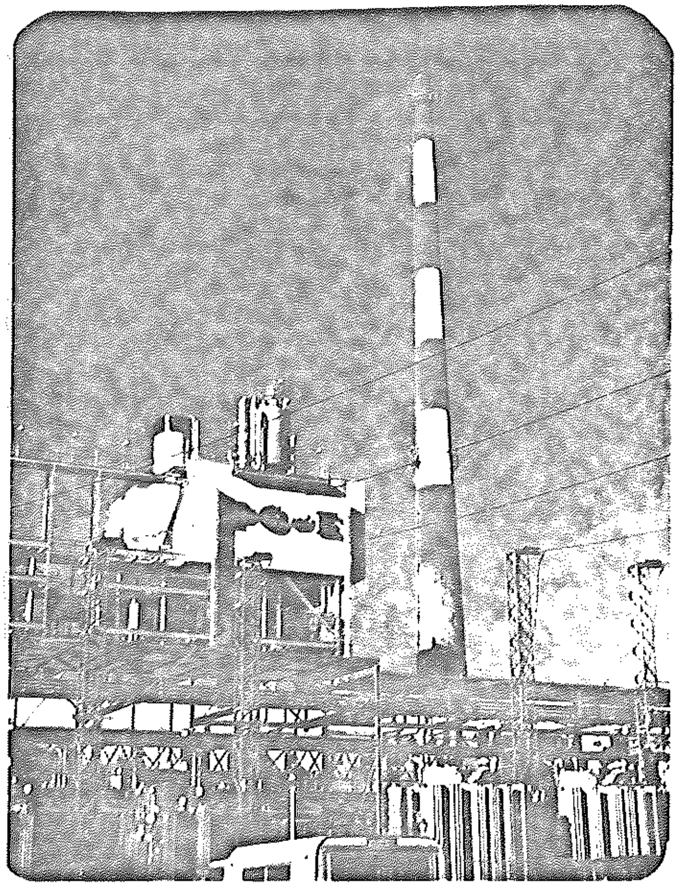


FIGURE 6: VENTILATION STACK

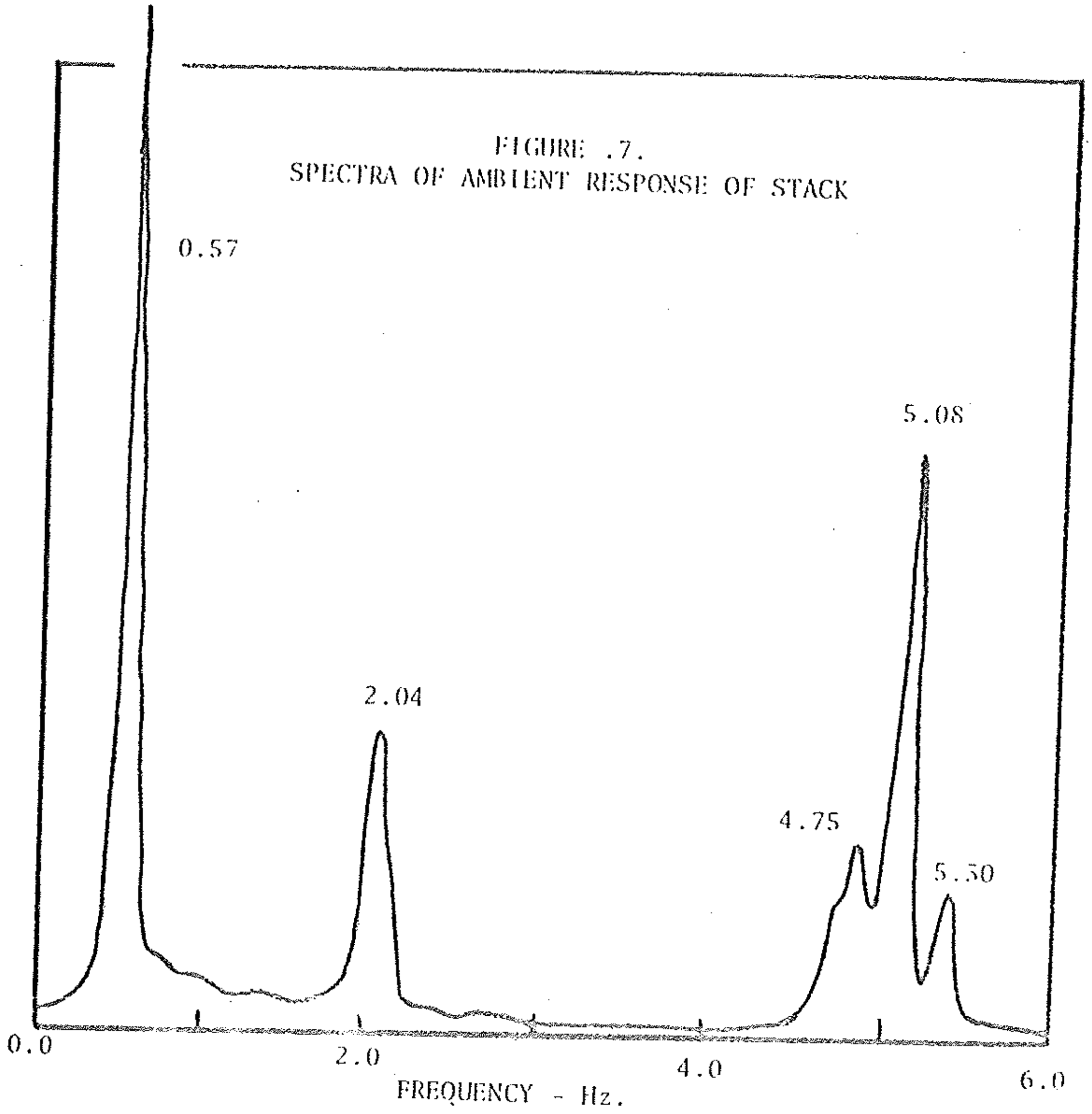
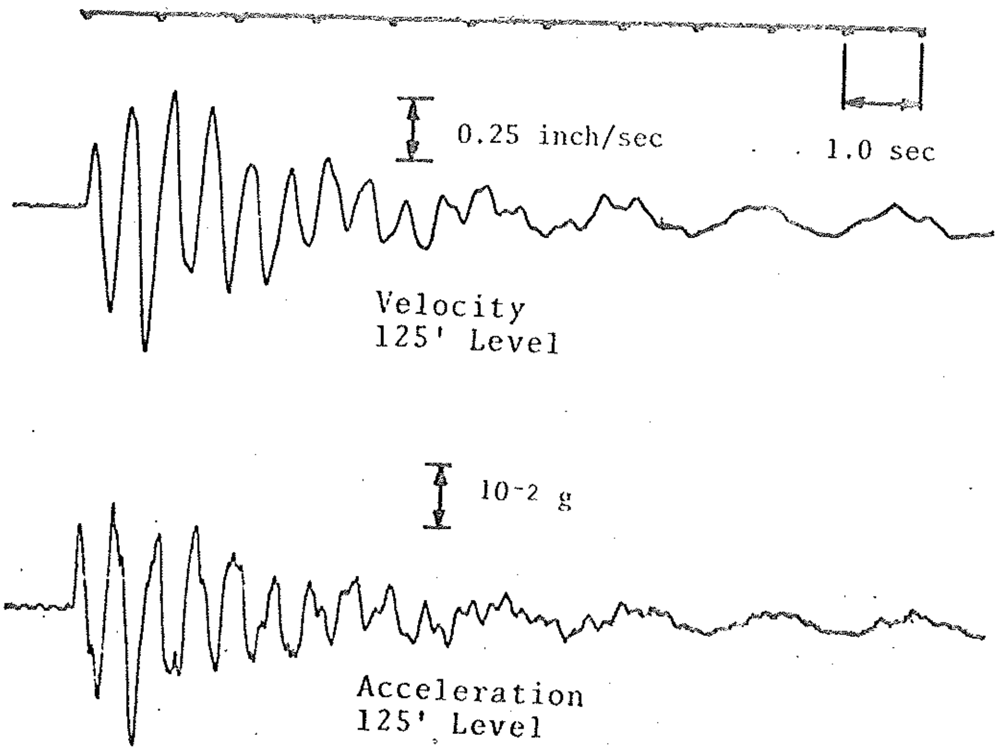


FIGURE .7.
SPECTRA OF AMBIENT RESPONSE OF STACK

Figure .8. SNAPBACK TEMPORAL RESPONSE



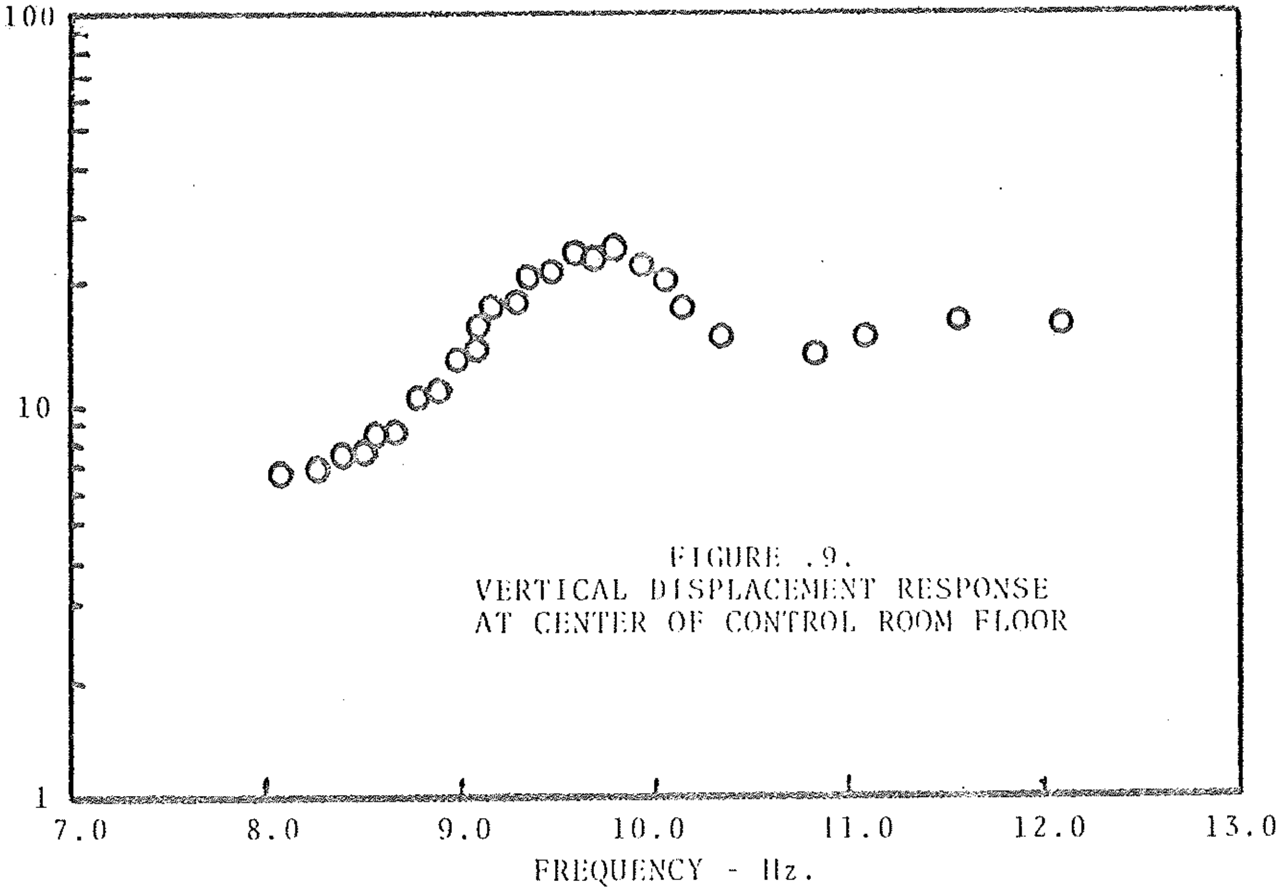


FIGURE .9.
VERTICAL DISPLACEMENT RESPONSE
AT CENTER OF CONTROL ROOM FLOOR

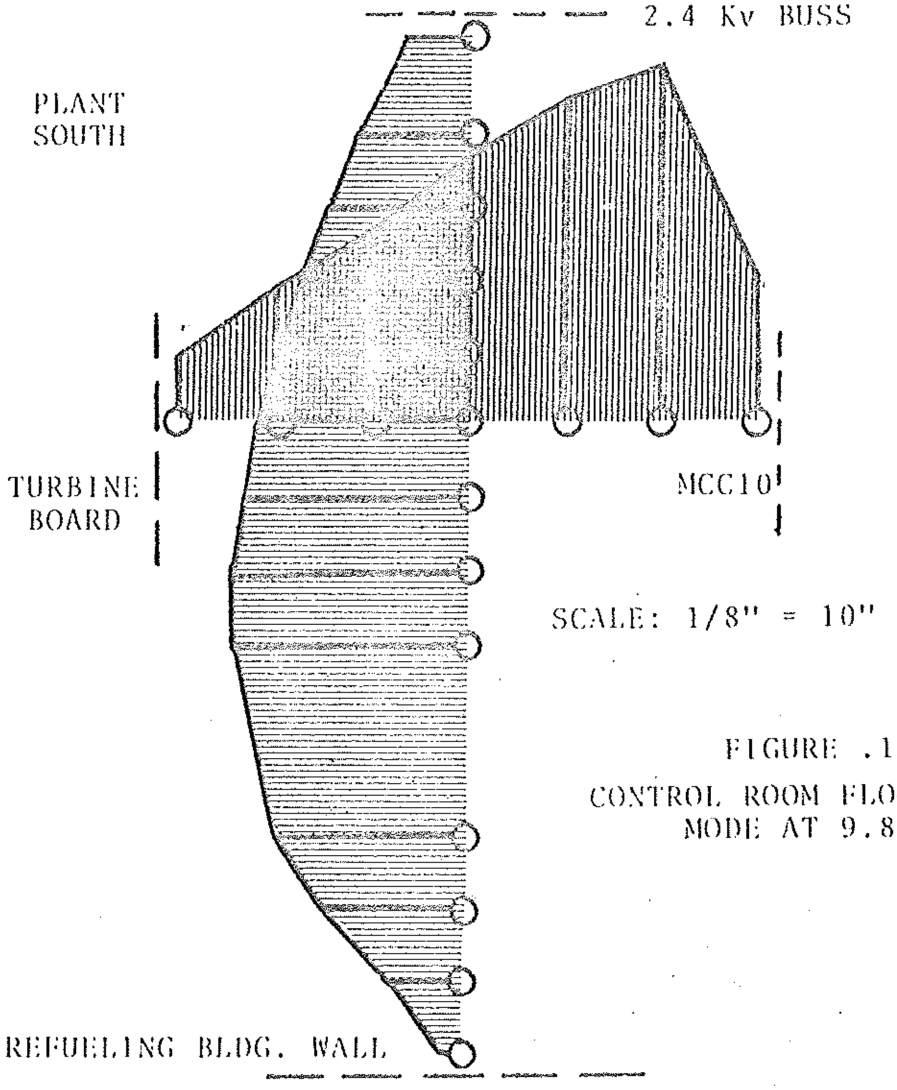


FIGURE .10.
CONTROL ROOM FLOOR VERTICAL
MODE AT 9.8 Hz.