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Methods and Benefits of Experimental Seismic Evaluation of Nuclear Power Plants

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ANCO Engineers, Incorporated

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1.0 ABSTRACT

This study reviews experimental techniques, instrumentation requirements, safety considerations, and benefits of performing vibration tests on nuclear power plant containments and internal components. The emphasis is on testing to improve seismic structural models. Techniques for identification of resonant frequencies, damping, and mode shapes, are discussed. The benefits of testing with regard to increased damping and more accurate computer models are outlined. A test plan, schedule and budget are presented for a typical PWR nuclear power plant.

2.0 EXECUTIVE SUMMARY

The goal of this study is to describe the technical and cost factors relevant to a decision on whether or not to use testing to verify and improve on the dynamic analysis and theoretical models of nuclear power plant containment buildings and internal equipment. Vibration tests at nuclear power plants have been conducted at over 30 sites and have provided valuable information on design adequacy, have demonstrated higher damping than allowed by regulatory standards, and have usually demonstrated increased seismic capacity of the tested facility. The techniques and justifications for such testing have been fully developed over the last ten years.

Vibration tests at the San Onofre Nuclear Generating Station (SONGS) were first conducted in 1969, following preliminary tests on several prototype and research reactor facilities. These tests concentrated on the containment structure and the primary coolant loop. The importance of soil-structure interaction was demonstrated as well as the presence of high damping ($\sim$18 percent) in the lower modes of vibration even at low (10^{-3} g) acceleration response. The studies on the coolant loops led to improved mathematical models and structural modifications to achieve greater seismic capacity. Vibration tests were more recently (1978) carried out on the Diablo Canyon Nuclear Power Plant in order to demonstrate greater damping and seismic capacity of equipment and piping systems. These data were helpful in establishing the adequacy of the plant in view of increased seismic design requirements (0.4 g to 0.75 g). Earlier vibration tests on other containments (such as SONGS) and the demonstrated high values of damping were used to justify higher values of damping (7 percent) at Diablo Canyon. An extended research program sponsored by the Federal Republic of Germany at the HDR nuclear plant near Frankfurt is providing information on the moderate-to-high level response of containment structures (10^{-3} to 10^{-1} g) and piping systems (10^{-1} to 10^{1} g). Damping of 5 percent was found at moderate levels of containment response. High level tests are scheduled for October 1979. Tests on one-twelfth scale containment models, sponsored by

EPRI, have been conducted to scaled accelerations of 0.3 g using buried explosives and eccentric mass shakers. The results indicate very high values of damping (10 to 20 percent) and the importance of nonlinear soil-structure interaction. Other test programs support these observations and are discussed in the report.

A variety of testing methods are available for exciting containment structures to any reasonably desired levels of response (10^{-1} to 10^{0} g). The most promising and field proven are eccentric mass sinusoidal vibrators (with forces up to 10^{6} lb) and the use of buried explosives (using up to several tons of explosives). Linear hydraulic actuators, impulsive shear rams, and rockets are also potentially useful, but have not been as fully proven out. Equipment can be tested by the above methods and also with snapback techniques, electromechanical vibrators, and the base motion caused by exciting the containment itself. If only equipment is to be tested, direct excitation of the equipment is preferable to containment excitation. Instrumentation for such testing is readily available. Data gathering, accuracy, and presentation are greatly enhanced by recent developments in computerized vibration analysis systems and portable real-time spectrum analyzers. The exact choice of testing method depends on the specific plant tested, soil conditions, surrounding buildings, goals of the project and other factors.

A more severe restriction than attainable levels of response in testing is the *allowable* level of response. Test programs on operational facilities must avoid amplitudes which could produce adverse regulatory effects (or other measure of "damage"). In conflict with this requirement is the desire to test to the highest response levels acceptable to demonstrate the maximum* damping possible and to investigate other nonlinear trends. ANCO test programs have, for example, lead to reductions in predicted seismic response by factors of 1.2 to greater than 2 (15 percent to 50 percent less response), depending upon system design, materials, erection, and boundary conditions.

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*Energy dissipation is typically amplitude dependent and has been observed to almost always increase significantly with test response level.

These reductions have been the product of nonlinearities as well as conservative design criteria applied to even low level response.

Herein it is argued that concern for equipment is a more restrictive test response requirement than concern for containment structures. In plants designed for low seismic areas, the authors feel that containment responses on the order of 50 to 100 percent of that to be generated by the predicted Operating Basis Earthquake (OBE) motion* are acceptable during testing. Plants designed for higher seismic inputs may be more strictly limited to a smaller fraction of their OBE due to concern for seismic Class III equipment. In any case the allowable levels of response appear to be greater than these required to demonstrate the validity of models and provide higher damping estimates.

A test program will typically involve measurement of damping values, resonant frequencies, and mode shapes. The variations in these properties with level of response is useful to the understanding of nonlinear properties. Parameter identification techniques can be used in the field or after the test to estimate these dynamic properties from response data. Other techniques, such as Bayesian identification, are useful to modify models or parameters of models (such as soil properties) in order to more closely match the identified system dynamic properties. These techniques have been fully demonstrated on a variety of structures including those from the aerospace industry as well as nuclear power plant structures and equipment.

Testing costs will vary considerably depending on the scope and goals of the test. Simple tests to estimate a few resonant frequencies and dampings on an uncomplicated piece of equipment can be carried out for less than five thousand dollars. Extensive research efforts involving both theoretical and experimental investigation on a containment and its internal equipment can cost well over a million dollars. Generally, the test program can be scoped such that the economic benefit of reduced down-time is several times the cost of testing. A procedure for test planning, budgeting, and scheduling and an example test are presented later in this study.

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*OBE free-field maximum accelerations are typically 0.1 g - 0.2 g at most U.S. sites.

3.0 REVIEW OF TESTING EXPERIENCE

3.1 Introduction

Vibration tests have been conducted at nuclear reactor facilities in the United States and overseas since 1965. These tests have been based on measuring either (1) the response to ambient vibrations, or (2) the response to forced vibrations caused either by mechanical vibrators, buried explosive charges, initial displacements ("snapback tests") or, in a limited number of cases, actual earthquakes.

The principal objective of these tests has been to verify seismic design calculations. Motivations for testing are:

(1) to gain insight into the dynamic response of systems which are difficult to analyze;

(2) to study nonlinear vibrations;

(3) to conduct "proof-tests" of certain components or structures;

(4) to measure specific dynamic parameters, e.g., eigenfrequencies, mode shapes and damping ratios;

(5) to improve computer models and modeling assumptions; and,

(6) to demonstrate seismic safety margins greater than indicated by theoretical analysis alone.

In the following subsections, seismic tests that have been performed by ANCO Engineers, Inc. and other organizations are reviewed, test results summarized and recommendations for future work made. The review is intended to be a sampling of typical projects rather than an exhaustive survey of the literature. The experience of and qualifications of ANCO to do seismic testing of nuclear power plants is presented. References and a bibliography of relevant literature is included at the end of this section.

3.2 Previous Seismic Tests of Nuclear Power Plants

3.2.1 Soil-Structure Interaction and Equipment Testing

An important aspect of seismic design is to determine the effect of foundations and the effect of soil-foundation interaction on structural response. The importance of this effect for massive structures such as nuclear power plants has been known for some time. However, it can also be an important factor in determining the response of heavy equipment installed on foundations. This was demonstrated during the explosive proof testing of a circuit breaker which weighed on the order of 15 metric tons. [24]* The circuit breaker was installed on a concrete pad having gross dimensions of approximately 10 meters long by 3 meters wide by 1 meter thick. The response of the circuit breaker, its foundation slab, and the free-field soil was measured during a series of tests where explosives buried in the ground were used to create high intensity ground motion. These tests indicated that the free-field response was greater than the response measured on the circuit breaker foundation slab.

Although the data are limited, some experimental tests related to soil-structure interaction have been done using both models and reduced scale structures. Typical of these is the work reported by Richart [25] where foundations of various sizes and geometries were subjected to forced vibration tests.

The physical significance of soil-structure interaction has been observed in both experimental tests and in actual recorded earthquakes. Duke and others [27] have reviewed seismograph records obtained during actual earthquakes and inferred the extent and significance of the soil-structure interaction. Such interaction effects have been observed in tests

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*Numbers denote references at the end of this section.

on full-scale nuclear power plants. In addition, strong interactions have been observed on heavy equipment and their foundations when subjected to strong ground motions produced by buried explosives.

Soil compliance effects on the earthquake response of nuclear power containment structures and internal equipment are a significant aspect of nuclear facility design. An analytical and experimental research program [26] to investigate *nonlinear* soil-structure interaction effects on nuclear power plants has been initiated by the Electric Power Research Institute (EPRI).

The primary motivations for this EPRI research program are:

(1) Current methods for incorporating soil-structure interaction in seismic design appear to be conservative. Preliminary studies indicate that the realistic incorporation of soil nonlinear characteristics can reduce in-structure response spectra by factors of two or more below conventional linear predictions.[28]

(2) Realistic nonlinear methods for treating the nonlinear characteristics of soils may permit the derivation of more realistic site response spectra than those resulting from current regulatory procedures. It is anticipated that lower design spectra will result for a specific site input.

(3) Studies of wave propagation and scattering in an elastic media indicate that these phenomena can reduce in-structure response spectra for such large structures as nuclear containment buildings. An experimentally validated numerical procedure for incorporating nonlinear properties in wave propagation in soil may lead to further reductions in equipment dynamic loads. The objectives include:

(a) to demonstrate, by experiment and analysis, the significance of nonlinear soil-structure interaction effects on the seismic response of nuclear power systems;

(b) to obtain high soil strain dynamic soil-structure interaction data for structures and embedments typical of nuclear containment structures;

(c) to develop fundamentally correct soil constitutive formulations for incorporating soil nonlinear effects in predictive techniques;

(d) to demonstrate the capability of predicting the salient features of high strain soil-structure interaction;

(e) to evaluate existing methods for determining the high strain properties of soils *in-situ*; and,

(f) to develop an experimentally validated procedure for incorporating nonlinear soil-structure interaction in the seismic design of nuclear power facilities.

The realistic treatment of nonlinear soil characteristics may suppress in-structure response spectra by factors of two or more, depending upon soil and structure characteristics. Reductions in equipment loading are of significance not only to future facilities but also (and perhaps of even greater importance) for existing nuclear power plants subject to new seismic design criteria. An experimentally validated method for demonstrating the seismic design margins existing for any given installation (arising from nonlinear interaction effects) could be decisive in the minimizing downtime losses and construction costs involved in a retrofit to increased seismic criteria.

Tests have been conducted with reinforced concrete models as large as one-tenth the size of a full-scale nuclear power plant containment building. [26] The models were subjected to a simulated earthquake produced by detonating up to 70,000 kg of buried explosives. The results indicate that nonlinear soil response is very important at higher levels of response (>0.1 g).

Soil-structure interaction has also been recognized as an important issue in overseas work. In Japan two experimental investigations were carried out in one project.[11] One was a full-scale test using the JPDR Plant and the other was model tests. Forced vibration tests using horizontal excitation for each model were carried out by means of an exciter installed on the roof slab (before and after backfill) to study the effect due to the backfill taking place around the model structure. The exciter was an eccentric mass shaker of the variable rotation speed type.

Three different soil conditions were selected. It was expected that different frequency vibrations for the three cases might happen as a result of the forced vibration test. However, no essential difference in frequency was evident.

Furthermore, the nuclear reactor enclosure of the JPDR has been instrumented with seismometers to measure vibrations of the structure and the ground during natural earthquakes. Results of measurements and calculations indicated that the response of the structure was considerably influenced by the earthquake response of the surface layer. The dominant frequency of the soil-structure system was observed to be 4.5 Hz.

The importance of understanding and correctly modeling soil-structure interaction phenomena is underscored by the critical nature of equipment safety. The reactor containment building filters and amplifies the ground motion caused by earthquakes. It is this motion which is the exciting force for equipment installed within the containment building. It is extremely important in equipment tests that the support and connections to the containment building and to other equipment be adequately modeled. During a testing program to determine the seismic response of electrical distribution equipment, forced vibration tests were performed on a large capacitor rack. Further tests were performed to determine the sensitivity of the measurements to minor changes in supports and field installation methods. The mounting bolts on the capacitor rack were loosened slightly--approximately one-quarter turn. This slight perturbation to the supports of the capacitor rack dramatically shifted the eigenfrequencies and modified the damping values and relative amplitudes of the modes.[24]

The difficulty in anticipating the effect of such changes, as well as more subtle changes such as aging, corrosion, modifications by field or maintenance personnel, makes it obvious that prediction of seismic response by purely analytical means can be subject to large errors.

When massive equipment is installed in a heavy structure, the possibility of interactions between equipment and the structure exist. Forced vibration of a containment building and of two steam generators indicated that the excitation of one steam generator caused a coupled response to occur in the second steam generator, although they were physically separated by a distance exceeding 100 ft.[3,7,24] The only coupling was through the building and through the interconnecting piping of the primary coolant loop. When the building was excited, each steam generator responded and energy was transferred back and forth between the two large (∿80 metric tons) steam generators.

Vibration tests have been conducted both on individual components and on full-scale reactor structures. Experience with actual earthquakes has been limited. To date, no commercial nuclear power plant has experienced the forces caused by a nearby major earthquake, except for the Humboldt Bay Plant which experienced a short duration 0.25 g earthquake without damage.[29]

A limited comparison of both test results and theory with data obtained during actual earthquakes has been made. The number of instances where this has been done are so few that no significant conclusions can be drawn. An example taken from one power plant will serve to illustrate the point.[24] The measured accelerations on a steam generator were found to be much higher than were predicted by an analysis using a dynamic model which had been constructed from experimental data. Upon review, it was found that both the model (which was based on linear theory) and the testing (which had been done at low levels) failed to take into account the effect of "seismic stops" which caused impacts when the steam generator movement exceeded the gap clearance. These impacts resulted in high acceleration levels in the steam generator vessel which were recorded by the seismic instrumentation.

3.2.2 ANCO Case Studies

Some examples of specific tests performed by ANCO will now be given. These case studies illustrate the methods, objectives, and benefits resulting from various types of seismic testing of nuclear power plant containment buildings and equipment.

Case Study No. 1: Containment Building Tests at HDR, Kahl, Federal Republic of Germany

A series of ambient, forced vibration, snapback, and low-level explosive tests were performed on the Heissdampfreaktor (HDR), a decommissioned nuclear power plant facility located in the Federal Republic of Germany.[2,10] These tests were used to determine the dynamic characteristics and response of the reactor containment structure and several piping systems under simulated seismic excitation. The primary concern was the identification of the critical eigenfrequencies, modal deformations, and damping values of each structural system tested.

The HDR is a nuclear power plant with a containment structure consisting of a cylindrical steel liner and a concrete outer shell. The structure is only slightly embedded in the soil and the liner and outer shell are structurally separate over much of their height. A two-dimensional finite element model, a three-dimensional lumped mass model, and an axisymmetric shell model were prepared prior to testing. Soil-structure interaction effects were included. A unique feature of these models was that the response of the structure to eccentric mass shakers at various locations was predicted prior to forced vibration tests.

Sinusoidal vibrators, snapback and buried explosive charges were used to excite the structure and several internal piping systems so as to estimate dynamic properties. The first mode of the containment was found at 1.3 Hz with about 5 percent damping at 10^{-3} g. The primary objectives of the low-level blast tests (<10 kg explosives) tests were: (1) to obtain additional dynamic soil data at the HDR site under conditions of increased strain; (2) to obtain basic data which could be used to predict the response of HDR when subjected to higher level explosive tests; (3) to determine if higher level tests are feasible and useful for dynamic analysis of the HDR site; and (4) to obtain information which can be used to develop a plan for higher level explosive tests that would not compromise the operational and design safety of a nearby boiling water reactor power plant.

It appears, based on the low-level tests, that high-level tests can be carried out safely and would yield important information concerning the nonlinear behavior of structures and the modeling of structures, piping, and equipment during strong ground motion seismic events. These additional tests along with higher level sinusoidal tests are currently planned for October 1979, and will be carried out by ANCO.

Case Study No. 2: San Onofre Primary Coolant System Studies, San Onofre, California

Forced vibration tests[6,8,17-20] were conducted at the San Onofre Nuclear Generating Station (SONGS). Tests were made on the reactor building and the primary coolant system during a refueling outage. Dynamic properties were identified and used to modify an analytical model.

The analytical model was used to study the response of San Onofre to earthquakes. The results indicated that additional seismic restraints on the primary coolant loop were desirable, and these were subsequently installed. The results also clearly indicated the significance of soil-structure interaction. The first mode of the containment was found at about 5.0 Hz with 15 percent damping at 10^{-3} g.

These tests were particularly important because they were the first forced vibration tests on a large nuclear power plant and because San Onofre was one of the first nuclear power plants to be constructed in a high seismic zone.

Case Study No. 3: Equipment Tests at Diablo Canyon, San Luis Obispo, California

Vibration tests of equipment at the Diablo Canyon Nuclear Power Plant near San Luis Obispo, California, were performed at the request of the utility, Pacific Gas and Electric Company.[30] The objective of these tests was to determine the dynamic properties of the equipment. Using these data and comparing them to theoretical models allowed improvements in these models and a more confident evaluation of the seismic capacity of the equipment. Extensive on-site dynamic testing of piping systems and safety related equipment was used to obtain experimentally validated dynamic models for extreme loads design assessment. These tests were part of a general review of the plant design. The review was occasioned by the need to re-examine the design of the plant in light of new seismic design criteria. *In-situ* testing proved to be an economical, rapid, and valuable adjunct to engineering analysis. In most cases damping at allowable test excitation levels (<0.5 g) exceeded regulatory allowed values.

Case Study No. 4: *In-Situ* Testing of Equipment at Humboldt Bay, Humboldt Bay, California

The seismic design of safety related structures, systems, and components at the Pacific Gas and Electric Company Humboldt Bay Power Plant Unit 3 was re-evaluated using present day methods of seismic analysis in response to a Nuclear Regulatory Commission (NRC) request.[9] Significant changes have occurred in the methods of seismic analysis of nuclear power plants since the original design of the Humboldt Plant. Previously, static analysis was used. However, dynamic analysis is now used for all safety related structures, systems, and components; structural amplification is included in defining input motions for equipment and piping located in structures. 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 a more rigorous seismic design input has been defined.

Evaluation of the seismic design of the plant and design of certain modifications was undertaken to provide the additional margin of safety required by present day methods of seismic analysis.

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 useful in giving direction to, speeding up, and giving confidence to analyses that were required to be performed for the seismic evaluation. On-site dynamic testing of over 40 structures and different pieces of equipment was done to obtain experimentally validated dynamic models for assessment of seismic design adequacy of this first generation nuclear power facility.

Testing was most useful in obtaining data to facilitate analysis of storage tanks, pumps and motors, and electrical panel enclosures. Testing of building structures provided more confidence in analytical models and to identify problem areas.

Case Study No. 5: KKP Piping Tests, Federal Republic of Germany

Forced vibration testing was performed on one of the three sections of piping comprising a major portion of the "Lagerdruckwassersaugleitung" (LDS) piping system at Kernkraftwerk Nord bei Phillippsburg (KKP), a PWR nuclear power plant, Federal Republic of Germany.[35] Testing was performed at the request of Technischer Uberwachungs-Verein (TUV) Baden e.V., Mannheim, which is the licensing authority for this nuclear plant.

The purpose of this experimental study was twofold: (1) to provide a benchmark case for comparison with the results predicted by linear-elastic finite element techniques; and (2) to qualify, and perhaps quantify, generalizations that may be made on the dynamic behavior of the piping systems.

A nuclear steam supply system is comprised of many piping systems which are directly related to the safe operation of the facility and very little experimental evidence exists to support their integrity under postulated seismic activity. Therefore, conservative modeling and conservative assumptions to limit the sum of operational and postulated accident-induced stresses have been imposed upon designers.

The piping system at KKP was excited by snapback techniques to about 0.5 g and the response measured and analyzed to yield estimates of resonant frequencies, mode shapes, and damping. The theoretically predicted first mode resonant frequency was 25 percent less than the measured value even after the "as built" conditions were incorporated into the theoretical model. The error was largely due to the actual system being stiffer than predicted. Damping in the lower six modes was higher than anticipated (as much as 9 percent rather than the assumed value of 2 percent). The damping in the higher modes was on the order of 2 percent. The two trends observed in the LDS pipe, increased damping and increased stiffness, tend to reduce earthquake response.

Case Study No. 6: Cooling Tower Tests at Rancho Seco, Sacramento, California

A 425 ft concrete hyperbolic cooling tower was tested by monitoring vibration response to ambient excitation.[1] The objective of the testing was to identify resonant frequencies, damping, and mode shapes significant to the seismic and wind excited response of the tower. The tower, constructed by Research Cottrell, is the east cooling tower for the Rancho Seco Nuclear Power Plant.

Testing consisted of placing accelerometers at various points on the tower and analyzing the time responses with a real time spectrum analyzer.

Average spectra were taken over time periods ranging from four to forty minutes and full range frequency from 0 to 2.5 Hz. Responses were on the order of 10^{-4} g.

The response of the tower consists of ovaling and breathing response as well as bending and shearing response. Each mode of vibration involved a combination of these responses. The tower was found to be very stiff compared to an office building of the same height. The first resonant frequency of the tower was 2.15 Hz compared to a typical building (425 ft high) with a first resonant frequency of 0.4 Hz. The tower damping was determined to be 2 percent. This damping is comparable of office building damping at the same level of response. Data from tests on similar large concrete structures suggest that the damping would increase at higher levels of response to about 5-10 percent at 1 g. This trend could be further verified using forced vibration techniques but has not been done.

3.3 Summary of Test Results

Experience with a wide variety of vibration tests at many nuclear power plants leads to the following conclusions:

- such tests can be done conveniently and quickly;
- they are economical and safe;
- they provide valuable information to confirm vital seismic design parameters; and,
- they give insight into parameters which cannot be calculated, such as damping.[4,23]

Confirming seismic tests of nuclear power plants in areas of high seismic activity would increase the reliability and accuracy of the structural analysis methods and would, therefore, lead to increased confidence in seismic analysis and design. The test results and the enhanced analysis capability would (1) help to heighten public confidence in and acceptance of nuclear power; (2) allow more economical designs; and (3) reduce the time required during the licensing review.

To date confirming seismic tests have been carried out on more than twenty nuclear facilities world wide. Examples of all major systems and equipment have been tested without problems. The systems tested and the test methods are summarized in Table 3.1. Based on the results of these tests it can be concluded that vibration testing of power plants is useful and feasible.

Several items require additional research and should receive consideration in future test programs. These research items include: (1) high level tests, (3) seismic instrumentation for nuclear power plants, and (3) contingency actions to be taken following an earthquake.

Perhaps of greatest importance is the need to conduct high level tests. The forcing levels used in testing should approach those of strong motion earthquakes. Methods are currently available which allow high level tests to be conducted in most instances.

High level tests are important because all structures and equipment respond in a nonlinear fashion to some extent. Tests to date indicate that both stiffness and damping may be expected to change as the level of forcing is increased. However, tests have been performed in which the stiffness increased for some types of equipment and decreased for others. In virtually all cases, damping increases as the level of excitation increases.[4] These effects should be studied at power plant sites where high level testing is feasible.

Seismic instrumentation in power plants requires review to determine if current instruments are adequate to provide data which can be compared to the plant seismic design following an earthquake. In the event of a moderate earthquake with no visible damage to the plant, it would be desirable to return the plant to operation as soon as possible. Procedures to do this efficiently while still protecting public safety are required and currently being considered.[31,32]

TABLE 3.1: PREVIOUS EXPERIMENTAL TESTS OF NUCLEAR POWER PLANT STRUCTURES AND EQUIPMENT

Item	Test Method*
Containment Buildings	
Steel, sphere	sv
Steel and concrete, cylinder	sv,b
Concrete, cylinder	sv,a
Electrical penetrations	st
Primary Coolant Loops	
Piping	sv,b
Steam generator (gas)	sv,b,sb
Steam generator (water)	sv
Steam generator (sodium)	b
Pumps	sv,b
Pressurizer	sv
Reactor Vessels	
Pressurized water reactor	sv
Boiling water reactor	a
Gas-cooled reactor	sv,b
Reactor core	sv,b
Reactor fuel element	st
Auxiliary equipment	
Circuit breakers	sv
Transformer	sv
Emergency diesels	sv
Fire protection equipment	st
Control panels	sv,st
Lightning arrester	sv,sb
Capacitor banks	sv,sb
Cable trays	sv,st
Cooling Towers	a

*Test methods: sv = structural vibrator
st = shake table
b = explosive blasts
sb = "snapback" tests
a = ambient

NOTE: References to these tests are given in references [13], [24], and [34].

3.4 Qualifications of ANCO Engineers, Inc.

ANCO Engineers, Inc. (formerly Applied Nucleonics Company) has considerable experience in vibration testing and analysis of nuclear power plants and this work comprises a large portion of the world experience. A selection of tests performed by ANCO is given in Table 3.2. ANCO has also performed state-of-the-art studies in the seismic analysis of nuclear power plants,[36] in the undergrounding of nuclear power plants,[33] and in parameter identification methods for structures.[34] We are currently involved in several major field vibration tests, including the high level containment and piping system tests at the HDR Reactor near Frankfurt, Federal Republic of Germany, and the piping system at Indian Point Unit I near New York City. ANCO has just completed extensive *in-situ* seismic re-evaluation tests at the Diablo Canyon Nuclear Power Plant. ANCO has also performed purely theoretical structural analysis on more than ten nuclear power plant structures.

TABLE 3.2: SELECTED ANCO EXPERIENCE IN STRUCTURAL DYNAMICS AND EARTHQUAKE ENGINEERING FOR NUCLEAR FACILITIES

Title/Client	Description
Nonlinear Earthquake Induced Soil-Structure Interaction of Nuclear Power Plants/Electric Power Research Institute	Technical management responsibility for multi-year analytical and experimental research program to evaluate significance of nonlinear interaction and to develop experimentally validated methodologies for incorporating nonlinear interaction in the seismic design of nuclear power plants. Primary function is to advance the state-of-the-art of seismic design of nuclear power plants. Responsibilities include program recommendations, technical direction, independent checking and monitoring, and selected parallel investigations; entails management of seven contracting organizations. The experimental phase of this research involved "simulated earthquake" excitation of five buried and embedded concrete nuclear containment structure models.
Earthquake Safety Evaluation and Dynamic Testing of Emergency Core Cooling System Piping, Fernkraftwerk Phillippsburg/ Technischer Überwachungs Verein-Baden, Federal Republic of Germany	Prepare dynamic models of containment structure and soil to determine 800 MWe nuclear power plant seismic response incorporating soil-structure interaction; develop piping system dynamic models for safety evaluation; conduct vibration testing on site to validate and modify dynamic models; perform piping and equipment earthquake response calculations and assess safety.
Diablo Canyon Dynamic Testing and Analysis of Equipment and Piping System/Pacific Gas and Electric Company	Perform extensive on-site dynamic testing of piping systems and safety related equipment to obtain experimentally validated dynamic models for extreme loads design assessment. Responsibilities included determination of eigenparameters; nonlinear response studies; data analysis; and model identification.

TABLE 3.2 (cont'd)

Title/Client	Description
Experimental Evaluation of Cable Trays and Electrical Conduit/Bechtel Power Corporation	Design and construct biaxial hydraulically driven shake table 5 meters by 12 meters in size to evaluate the dynamic properties and failure modes of various system designs. Table capacity of 5 tons at 2 g achieved for simulating floor response time histories in nuclear power plants. Program purpose was evaluation of design parameter influence on seismic capacity and establishment of simplified and economic designs.
Seismic Qualification of Equipment and Structures, Humboldt Bay Nuclear Generating Station/Bechtel Power Corporation	Conduct on-site dynamic testing of over 40 structures and equipment to obtain experimentally validated dynamic models for assessment of seismic design adequacy of first generation nuclear power facility. Responsibilities included close coordination with A/E responsible for design of system modification.
Earthquake Safety Evaluation of Primary and Emergency Cooling Piping and Equipment, Gemeinschaftkernkraftwerk I/Technischer Überwachungs Verein-Stuttgart, Federal Republic of Germany	Dynamic analysis of structures, equipment, and primary and emergency cooling systems for an 800 MWe PWR. Seismic safety evaluation included study of buried piping and river structures.
Seismic Assessment of Underground and Bermed Nuclear Power Plants/Aerospace Corporation	Dynamic analysis of alternatively configured nuclear power facilities; assessment of seismic implications as a function of site conditions and depth of burial; evaluation of the applicability of surface placement methodology to subsurface facilities; examination of topological conditions on response characteristics.

TABLE 3.2 (cont'd)

Title/Client	Description
Dynamic Analysis and Testing of Nuclear Power Plant Piping Systems/Electric Power Reserach Institute	Dynamic analysis and testing of five piping systems ranging in diameter from 15 cm (6 inches) to 75 cm (30 inches) and including primary, secondary, and auxiliary systems at a nuclear power plant. Purpose: to examine nonlinear effects at moderate response; to establish a large damping data base on a range of piping sizes; to develop benchmarks for computer code verification; to assess the importance of nonlinear effects in the design of piping for loads arising from seismic, waterhammer and other dynamic loads.
Seismic and Tornado Analysis of Standby Cooling Towers, Grand Gulf Nuclear Power Station/Ceramic Cooling Tower Company	Dynamic analyses of structures, piping systems and mechanical equipment comprising ultimate heat sink cooling towers for Grand Gulf Nuclear Power Station.
Dynamic Testing and Seismic Analysis of Containment Building, and Primary Coolant Loop Piping and Equipment, San Onofre Nuclear Generating Station/Southern California Edison Company	Perform vibration testing on structures and all three primary coolant loops. Predict response of system to Safe Shutdown Earthquake. Compare dynamic response to low level seismic excitation to theoretical predictions.
Dynamic Testing of Primary Coolant Loop Equipment, Rancho Seco Nuclear Generating Station/Bechtel Power Corporation	Perform ambient level vibration testing of piping and equipment. Identify major source of operating condition vibratory excitation of system.
State-of-the-Art Assessment of the Seismic Design of Nuclear Power Plants/Electric Power Research Institute	Evaluate current and near-term methods; review available dynamic response data pertinent to soil-structure interaction, containment structure dynamics and equipment dynamics. Identify research areas with potentially significant impact on nuclear power plant seismic design.

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4.0 SUMMARY OF TESTING METHODS

4.1 Introduction

Many testing methods evolved in recent years would be sufficient to excite a nuclear containment structure so that the dynamic characteristics of the structure could be identified.[15] Each method relies upon monitoring and analyzing the response of the test structure to a known or idealized forcing function. These forcing functions arise from (1) natural events such as ambient vibrations due to local traffic, wind and distant seismic events; and (2) applied loads such as impulses, sinusoidal varying loads and randomly applied loads. This broad spectrum of forcing functions may be categorized into three groups, those which are transient in nature, random in nature, and steady-state in nature.

The measurement of resonant frequencies, mode shapes and damping ratios is the primary goal of most testing regardless of the testing technique used. Most testing is carried out with some initial estimates of the structural response and of the dynamic characteristics. These estimates may come either from a sophisticated computer analysis or from experience and previous testing. The anticipated response will play a role in the decision as to what testing method will be used.

In the following sections the current methods of transient response testing, blast testing, and steady-state sinusoidal response testing will be reviewed. The methods will be examined in a theoretical sense and a practical sense with a discussion of both the merits and drawbacks of each. Ambient testing will not be further discussed as its use is not warranted for soil-structure interaction (except as it presents a lower bound to damping estimates). Ambient methods can be useful, however, for equipment testing and for structural modes not involving soil-structure interaction or other nonlinear phenomena.

4.2 Transient Testing

Several methods can be used to cause transient response of structures. These include response to earthquakes or other ambient excitation, snapbacks, impulsive loadings and nearby detonation of explosives.

In snapback testing, a static force is applied to the structure causing an initial displacement. The force is suddenly released and the structure undergoes free vibration with the initial displacement as the initial condition. This method has been successfully used to test large exhaust stacks,[10] heavy equipment including steam generators,[11] and piping systems.[12]

A method of applying the force and a method of quick release are required for snapback testing. Winches, cables, cranes or hydraulic rams can be used to apply the force; high speed hydraulic valves, unlatching mechanisms or frangible links (which fail at a known force) can be used to release the force.

The level of response in snapback testing is dependent on the initial displacement. For individual component testing the level of response attainable is limited only by available force application. Therefore, the snapback method is particularly useful for component tests. However, the snapback method would not be practical to use for testing of a full-scale structure such as a reactor containment vessel.

In practice, it is sometimes difficult to isolate modes of vibration of interest because the method tends to excite more than one mode at a time. Pre-analysis and experience as well as repeated tests with force application at different locations may be necessary for effective isolation of individual modes.

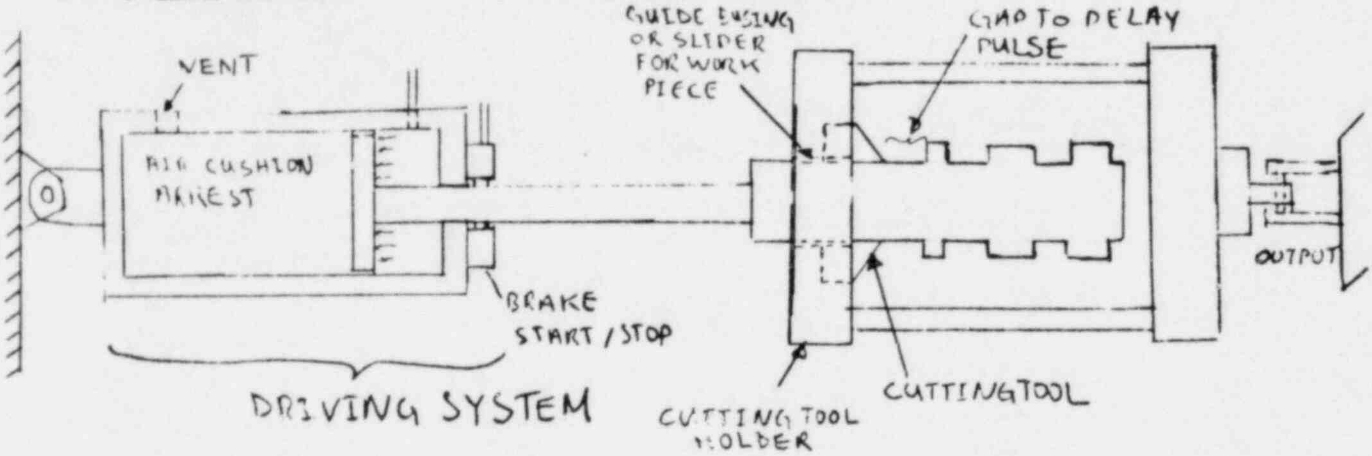
Impulse loadings with rubber mallets, hammers, or "manual excitation" are often sufficient to excite the fundamental modes of vibration of mechanical equipment and small buildings. A single person running with quick starts and quick stops can, in a 20-story building, produce response greater than the ambient vibration level.

Two impulsive loading methods which can generate higher responses than rubber mallets or manual excitation are mechanical pulse generators and chemical rockets. Mechanical pulse generators produce force profiles by drawing metal bars with variable cross sections through a cutting tool.

The force profile or wave form is dependent on cross section of the drawn metal bar.

A schematic diagram of a mechanical pulse generator is shown below.

A SCHEMATIC CONFIGURATION OF PULSE GENERATOR:



The force time history is dependent on three variables:

(1) the relative velocity of the cutting tool and the drawn bar;

(2) the specific cutting energy (which, at high speeds, is dependent only on the type of material and the cutting angle); and,

(3) the cross sectional profile of the bar.

Laboratory pulse generators have been used to generate force wave forms comparable to theoretical predictions[1] and have been used to test a 200,000 lb electrical panel.[2] Earthquake testing of the panel was not done but rather shock loading due to nuclear attacks were simulated.

There is not, however, extensive experience with mechanical pulse generators either in the laboratory or in the field. This lack of experience is one drawback on the use of the method for practical seismic testing of full-scale structures. Other possible difficulties in using the method include:

(1) the large cost of generator fabrication and placement;

(2) the large power requirements; and,

(3) the large and localized reaction loads transmitted to the structure.

Chemical rockets produce forces by the high velocity ejection of chemical matter. The chemical rocket is attached to the structure and the reaction to ejection transmitted to the structure.

The types of propellants include hydrogen and oxygen as well as various solid propellants. Large thrusts of 50,000 lb and 0.5 sec duration are attainable for single rockets. Larger durations of 20 sec are possible but with lower thrusts of approximately 5,000 lb. Rockets can be attached in parallel to produce larger total thrust. Typical performance parameters are given below.[4]

Specific Impulse (sec)	Maximum Temp. (°F)	Thrust to Weight Ratio	Duration	Specific Power (hp/lb)	Typical Working Fluid
200 to 480	4,500 to 7,800	10^{-2} to 100	Seconds to few hours	0.1 to 1,000	H_2 and O_2 or other fuel and oxidisers

Chemical rockets are inexpensive and have been used in the past in tower tests.[3] However, there is a lack of reported recent experience with chemical rockets for structural testing either in the laboratory or in the field. This lack of experience limits the practical use of the method. Other difficulties in using the method include:

(1) delay in the ignition of the rockets or lack of ignition in multiple installations due to burnt wires;

(2) high local reaction forces transmitted to the structure;

(3) smoke;

(4) expensive preparation; and,

(5) possible explosive safety hazards.

Nevertheless rockets may be used in testing of containments. The HDR tests using sinusoidal vibrators, snapback, and buried explosives will also use rockets to simulate aircraft impact.[12] Figure 4.1 illustrates the rocket unit to be used and its force/time properties. Twelve such units will be used and fired simultaneously.

4.3 Use of Buried Explosives

One method which has promise for high level tests of full-scale structures and equipment is buried explosive charges. By proper placement, sizing, spacing, and timing of the charges, it is possible to vary the ground motion amplitude, frequency content, and duration over ranges typical of earthquake ground motions. The first application of this method to a nuclear power plant was done in 1969 at the Enrico Fermi Power Plant.[5]

In this early work four critical questions were addressed:

(1) Is blast testing feasible from an economic point of view?

(2) Can it be done safely?

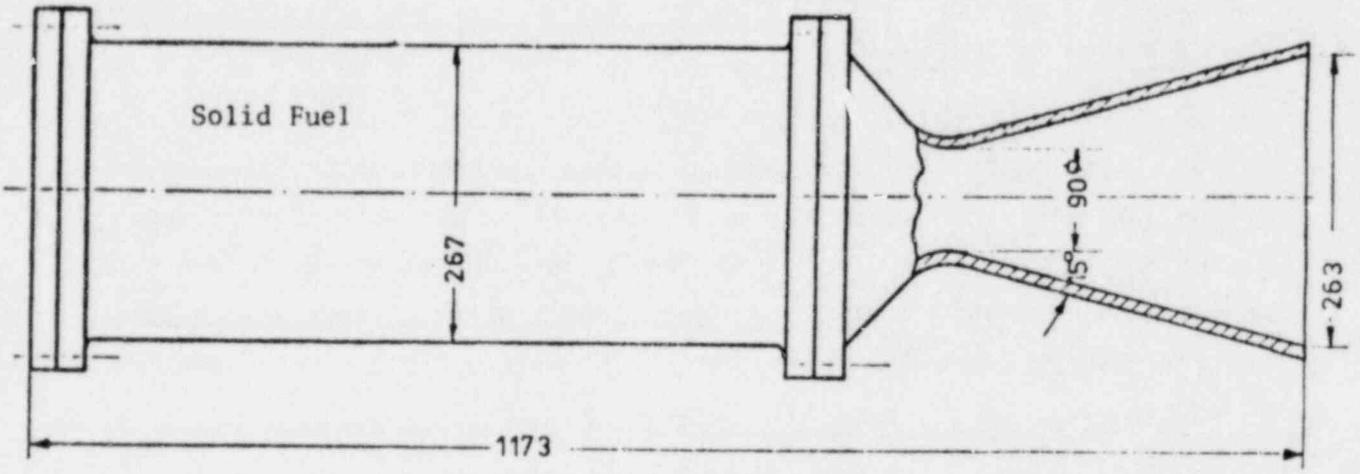
(3) Can earthquake-like ground motions be produced?

(4) Can it be extended to large full-scale structures?

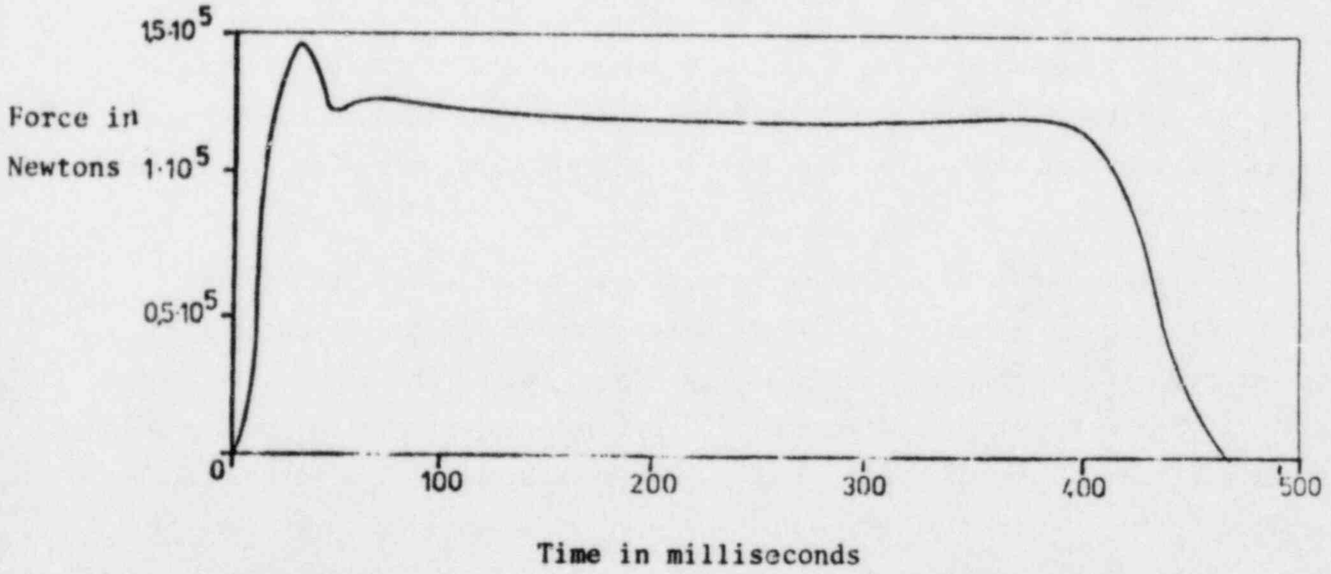
The early work indicated that the answers to all of these questions was *yes*. Costs were found to be comparable to or less than forced vibration tests. And buried explosives are capable of producing very high levels of response.

Safety was achieved by proper spacing and burial of the charges to prevent cratering and ejection of debris. By using multiple delayed charges, it was possible to enhance low frequency ground motion and extend the duration of ground motion. Durations of several seconds, equivalent to the high level portions of recorded earthquakes, can be achieved. The method can be applied to full-scale structures and was used at tests of a large nuclear power plant in Oak Ridge National Laboratory in 1970.[6] During the

FIGURE 4.1: ROCKET FOR USE IN HDR
CONTAINMENT TESTS



(dimensions in millimeters)



Oak Ridge tests, up to one ton of dynamite was used at distances of 250 to 300 ft from the containment building.

A review of defense literature on explosive effects indicated that acceptable correlations with experimental data existed and could be applied to seismic testing.[7,8] Test accelerations were proportional to the factor $W^{1/3}$, where W is the charge weight. Other findings of this literature review were:

(1) the depth of charge burial required and crater size required for specified ground motion could be predicted satisfactorily;

(2) the ground response is strongly dependent on soil properties, with wet or damp soils causing greater response;

(3) the effect of distance and depth can be modeled by scaling laws; and,

(4) the condition of the soil (disturbed vs. undisturbed) is important.

Besides the defense literature, two other general categories of information exist. The first category included numerous measurements of the effects of quarry blasts on structures in the vicinity. These are not generally useful since they report peak response values but contain no information about frequency content, duration, or soil properties.

The second category includes underground nuclear weapon tests. While these tests are extensively instrumented and analyzed, most of the data are not useful because it is for large charges, deeply buried and located far from the measuring equipment. Extension of the data to conventional explosives of interest to seismic simulation does not appear to be fruitful.

A more recent review of the literature has been provided by Higgins and his associates.[9] In addition to reviewing the older literature, they have examined newer work and have investigated the actual mechanisms by which explosive energy is coupled into and propagated through the soil.

Work has been carried out in three new promising areas using explosives:

(1) creating specified ground spectra for testing foundations with massive equipment items;

(2) creating specified (scaled) high level ground motions for testing up to one-tenth scale nuclear power plant containment buildings;[13] and,

(3) using explosives to perform high level tests of a German nuclear power plant.[12]

Explosives have also been used to test other structures, including reactor piping system, model buildings, and reinforced earth retaining walls.[15]

Seismic simulation tests using buried explosive charges is a proven, viable technique. Structures can be excited to peak levels of response ranging from 10^{-4} g to 10^{0} g, depending on the charge size and range. Test variables can be controlled within certain limits and predictive methods are available. The main safety considerations are avoiding underground piping locations and placing charges to avoid ejection of soil and debris. Experience indicates it is often possible to excite one structure in the midst of several others, but safety, insurance, and "political" problems may arise if other critical structures are within a few hundred yards of the tested structure.

Important to the success of the tests is proper selection and placement of instruments through knowledge of soil conditions, proper selection and handling of explosives, and a carefully thought-out and controlled test program.

In concluding, it should be pointed out that, more than any other test method, use of buried explosive charges resembles actual earthquakes. The energy is transmitted through the soil to the foundation. Soil-structure interaction effects are present. All systems are excited (buildings and equipment). Nonlinear effects and damping can be studied by gradually increasing the charge size. At the same time, information on soils can be obtained.

4.4 Sinusoidal Testing

The steady-state sinusoidal forced vibration test uses one or more structural vibrators placed at appropriate points on a structure. The response of the structure is measured at points of interest with accelerometers or other transducers, while the frequency of the vibrators is varied in increments over the desired frequency range. At each incremental frequency the vibrators are held at a constant frequency long enough for all transient effects to decay so that only the steady-state response of the structure is recorded.

For forced vibration tests several different types of vibration generators are available. For eccentric mass vibrators the force is produced by rotating eccentric masses or "baskets" about an axis. The force is changed by adding weights to the baskets, or otherwise altering the eccentric mass. The force is also varied by changing the rotation frequency.

The force generated by an eccentric mass vibrator is given by:

$$F(t) = mr\omega^2 \sin\omega t$$

where

mr is the eccentricity; and,

ω is the rotational frequency.

For a given "mr" value, the force varies as the square of the frequency. The maximum force from a vibrator is limited in order to prevent excessive stress in the vibrators or excessive power requirements. Table 4.1 lists the performance and specifications of several typical eccentric mass vibrators. Note that vibrators can use two counter rotating arms to produce unidirectional forcing or a single arm for omnidirectional (rotating vector) forcing. Figure 4.2 illustrates the nature of a large eccentric mass vibrator.

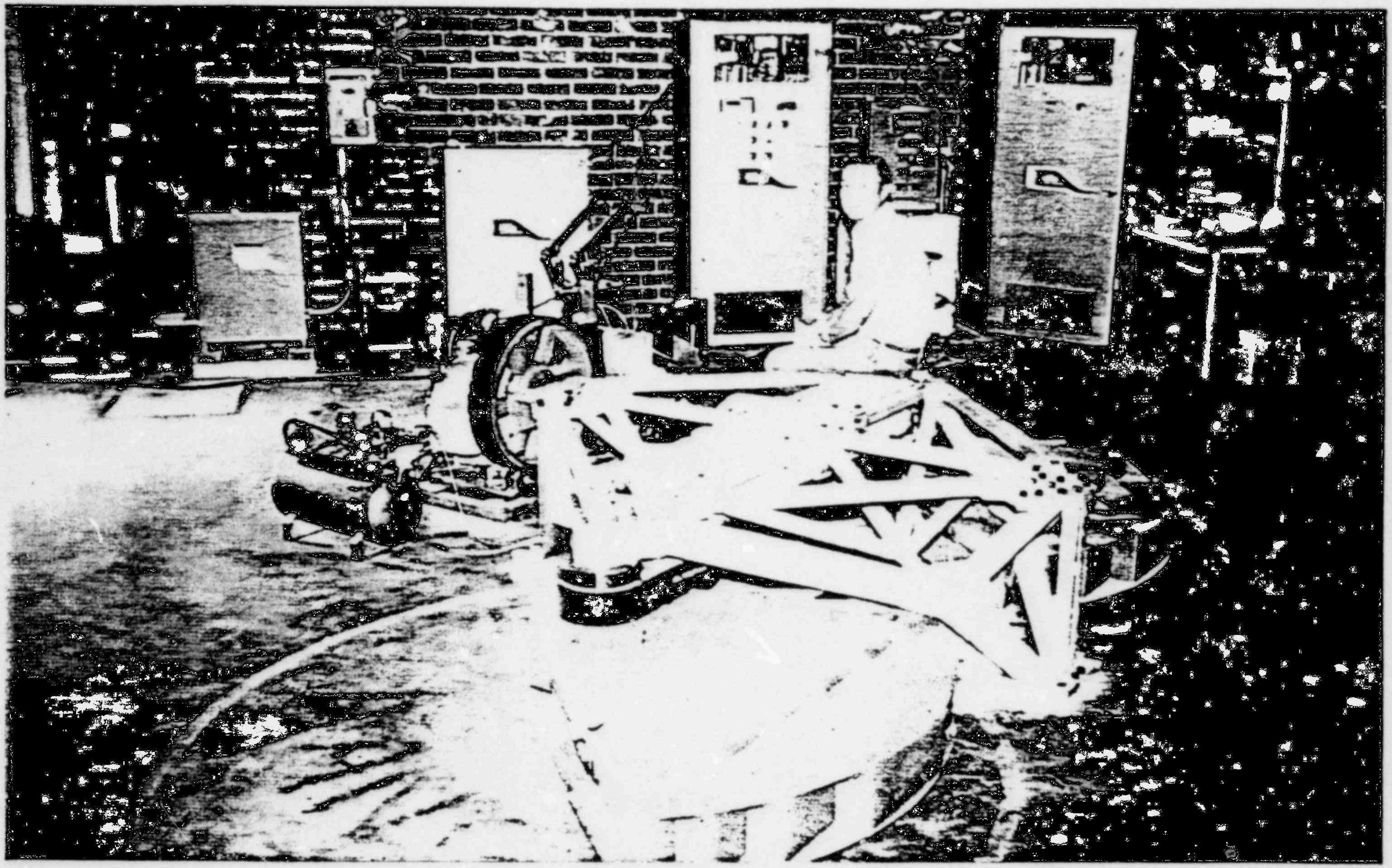
The vibrators are driven by motor-controller systems. The control system is usually a solid-state design which is temperature stabilized and

TABLE 4.1: TYPICAL ECCENTRIC MASS VIBRATORS

Designation	Max. Force (Newtons)*	Min. Freq. for Max. Force	Upper Limit Frequency (Hz)	Eccentricity (kg-m)	Mass of Vibration (kg)	Input Power (kW)
MK-11 ANCO	40,000	100	100	0.1	10	1.5
MK-12 ANCO	40,000	40	100	0.5	40	1.5
MK-13 ANCO	40,000	6	20	30.0	150	1.5
MK-14 ANCO	40,000	1.5	10	370.0	400	1.5
MK-15 ANCO (2 Synchronized Units)	1,000,000	2.5	30	4,000.0	8,000	75.0
EERI-CIT (4 Synchronized Units)	90,000	2.5	10	360.0	3,000	12.0
USSR W-2	800,000	3.7	8	1,560.0	7,700	50.0
USSR W-3	2,000,000	3.5	10	4,000.0	13,000	100.0
Japan CRIEPI (3 Synchronized Units)	4,000,000	10.0	20	1,500.00	∿20,000	100.0

*4.5 Newtons ∿ 1.0 lbf

FIGURE 4.2 LARGE ECCENTRIC MASS VIBRATOR (ANCO MK-15)



capable of maintaining the vibrator frequency within 0.1 percent of the desired value. An additional capability is an automatic sweep of select frequency ranges.

Linear hydraulic, reciprocal hydraulic, and electro-dynamic actuators also exist. Hydraulic systems are not as portable as eccentric mass vibrators but, along with electro-dynamic units, can supply other than sinusoidal forcing. Electro-dynamic units are typically of much smaller capacity than other types of vibrators, but are the most easily synchronized for multiple shaker applications. Hydraulic and electro-dynamic shakers operate by pushing on a reaction mass or a "strong wall." These vibrators are also more easily used to produce sine beat or fast sweep forcing. Typical units are described in Table 4.2. Eccentric mass vibrators typically require less input energy than linear hydraulic units as the "flywheel" effect of the former reduces the peak power required for control.

As a guide to detailed sinusoidal testing, to verify that no significant range of frequencies has been overlooked, and to establish the correct attenuator settings for each recording channel, the first step in a test is to make a "sweep" of the entire frequency range attainable with a given setup. During the sweep the frequency of vibration is gradually but continuously varied and the response is continuously recorded at some slow recording speed. The envelope of the resulting record corresponds to the desired response curve. The subsequent detailed testing is then concentrated in those frequency ranges which are of most interest.

Experience indicates that, in order to define lightly damped peaks, it is necessary to obtain at least five points within the bandwidth ($2\beta\omega_n$) of the peak. For 1 percent damping this requires a frequency step size of 0.4 percent, well within the capability of typical vibrators.

Sinusoidal vibrators, especially eccentric mass units, have been used in numerous nuclear power plant containment and conventional building tests. The techniques are well proven out and are capable of excitation levels up to 1.0 g on containment structures. Smaller units have also been used extensively in testing of equipment and components.

TABLE 4.2: TYPICAL ELECTRICAL AND HYDRAULIC VIBRATORS

Designation*	Maximum Force (Newtons)	Minimum Freq. for Maximum Force (Hz)	Upper Limit Frequency** (Hz)	Mass of Vibrator (kg)	Power (kW)
Sandia Hydraulic (Linear Inertial Mass)	56,000	2	50	8,800	64
Zonics Hydraulic ES-302-1 (Linear Inertial Mass)	9,000	20	200 (Useful to 500)	318	8
Zonics Hydraulic 1306 (Actuator against strong wall)	90,000	0	10 (Useful to 300)	35	25
Boeing Hydraulic (Linear Inertial Mass)	300,000	-	-	30,000	300
Acoustic Power Systems Electrodynamic (Either inertial mass or strong wall, ±8 cm stroke)	133	0 With strong wall	20 (Useful to 200)	36	0.13
Prodera Electrodynamic (Either inertial mass or strong wall, ±1.5 cm stroke)	2,000	0 With strong wall	50	155	1.75

*Manufacturers listed are typical of several in the market.

**Indicates upper limit at full force. Many vibrators can be used at higher frequencies, as indicated, at reduced force.

4.5 Summary

Methods for transient response testing and for steady-state testing include snapbacks, mechanical pulse generation, rocket propulsion, buried explosives and sinusoidal vibrators. The applications of and the merits and drawbacks of these techniques have been discussed.

One or more of these methods will be used during a seismic test of a nuclear power plant. Which methods will be used depends in part on the specific goals of the test plan, anticipated structural response, cost, safety considerations, ease of application and plant configuration and site condition.

A rating of each method for 11 test parameters is provided in Table 4.3. It has been assumed that a containment structure weighing 30×10^6 lb with 10 percent damping is to be tested. The ratings are a result of ANCO's considerable experience is both laboratory and field testing using many of the methods, extensive literature search and discussions with other organizations.

A method capable of high response levels and which is field proven is needed for practical seismic testing of nuclear power plant reactor containments. It is obvious from Table 4.3 as well as previous discussions summarizing past testing that sinusoidal testing and buried explosives are the most suitable, being both practical and economical. Mechanical pulse generators and rockets show promise but, as yet, are not proven for field use.

TABLE 4.3: QUALITATIVE ASSESSMENT OF TESTING METHODS
(Assuming 3×10^7 lb Test Object, $\beta = 0.10$)

Excitation Technique / Criterion or Test Objective	Transient Excitation					Sinusoidal or Random Excitation			
	Snapback	Pulse Generator	Rocket	Blast	Earthquake	Ambient	Eccentric Mass	Hydraulic	Electro-Dynamic
1. Resonant Frequencies	G	G	G	G	F	F	E	E	E
2. Damping Ratios	G	G	G	G	F	P	G	G	G
3. Mode Shapes	G	G	G	G	F	P	E	E	E
4. Nonlinear Trends in f_i, β_i	G	?	D	G	P	P	E	E	F
5. Achievable Peak Response (g) (available hardware)	10^{-2}	10^{-2}	10^{-2}	10^{-1}	10^{-1}	10^{-4}	10^{-1}	10^{-1}	10^{-3}
6. Test Repeatability	G	G	F	F	P	P	E	E	E
7. Ease of Data Analysis	E	G	G	G	F	F	E	E	E
8. Relative Cost	M	H	H	M	L	L	M	M	M
9. Availability of Forcing Hardware	E	G	F	E	P	E	E	E	G
10. Adverse Environmental Effects	L	L	M	M	H	L	L	L	L
11. Degree to which method has been proven practical	M	L	L	H	L	L	H	M	L

E = Excellent
G = Good
F = Fair
P = Poor

H = High
M = Moderate
L = Low

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5.0 ALLOWABLE LEVELS OF RESPONSE

5.1 Introduction

The safety requirement for dynamic testing of a nuclear plant is straightforward; response amplitudes which might damage or otherwise impair the licensability of the subject plant must be avoided. One may proceed through a series of steps of increasing rigor to demonstrate the acceptability of the planned loading conditions, using arguments ranging from previous experience and engineering judgment to detailed pre-test dynamic analyses. In establishing load acceptability one might consider:

(1) the specimen condition during testing (e.g., internal pressure of piping systems);

(2) loads the specimen saw in construction for reasonability arguments (e.g., persons standing on 6 in. piping lines to install supports, loads in transporting equipment to a site);

(3) simplified hand calculations to show that anticipated test response would be far less than that associated with an Operating Basis Earthquake* (OBE);

(4) detailed dynamic evaluations using computer models and subsequent loads assessment according to such standards as the ASME Boiler and Pressure Vessel Code; and,

(5) monitoring during tests.

The completion of steps (1) through (3) are sufficient and cost effective provided that low level response data are acceptable. For cases where moderate to high level response is sought, it is necessary to complete step (4) and to implement suitable monitoring methods (step 5) to check response amplitudes during testing.

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*That level of earthquake excitation during which the plant is expected to keep operating; an event which might occur several times in a plant's lifetime (with typical estimates being 5 to 20 occurrences).

High amplitude test data are desirable because response characteristics that are amplitude sensitive are important in assessing power plant earthquake response. Current analysis procedures do not explicitly treat such important nonlinear behavior as the increased damping (energy dissipations) that has been observed as a function of increased amplitude in piping systems, structures, and in soil-structure interaction.[1] Instead, conservative procedures* are used which over-estimate system dynamic response.

High amplitude testing is achievable by available test methods; however, damage to the system, both literally and in terms of licensability must be avoided. Where high level testing of a plant is planned, ANCO's approach has been to limit the subject system to levels which would lead to combined stresses less than those associated with the postulated OBE loading for that component in that plant.

Plants under construction and commissioned and decommissioned nuclear power plants have been tested to date. These plants have not been operating during the tests. A shutdown plant may be in either a "hot" or "cold" condition. The condition of the plant will determine, in part, possible test inputs. Because cold plants typically have fewer loading conditions than hot plants, it is anticipated that the test loadings can be larger for cold plants. An operating plant would also pose a severe radiation and thermal environment on the test crew and equipment. There is little reason to believe that the "hot" or "cold" or operating/not operating condition would significantly effect tests on the containment structure. Internal equipment such as piping with gaps and snubbers might be effected, but with due experimental consideration the "hot" condition can be closely simulated without operating the plant.

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*Conservative procedures assume a maximum of 2 percent of critical damping in piping system analysis. This compares to the 8 to 10 percent critical damping measured in ANCO tests. Similarly, soil-structure interaction is conservatively treated using linear analysis methods.

5.2 Containment Structures and Internal Equipment

For containment structures, test amplitudes have typically been restricted to amplitudes much less than those that would be associated with a subject plant's OBE. This is necessary to eliminate serious concern for Category III equipment. Peak response levels varying from 10^{-3} to 10^{0} g are possible using sinusoidal forced vibration and buried explosive charges. The output capability of sinusoidal vibration equipment has, until recently, been the common limitation on containment response in tests rather than any concern for over-driving the structure and its internals. Only when using explosive techniques or when using the largest vibrators available is serious concern with structure over-driving necessary.

When one wishes to achieve the highest containment response possible consistent with plant licensability, response should be limited to a fraction of the containment's OBE response. That is, floor response spectra associated with the testing must be less than the OBE spectra; otherwise, it is necessary to demonstrate that the OBE spectra are very conservative* and elicit regulatory approval such that the planned testing amplitudes will have no subsequent adverse impact.

The following equipment definitions are used in subsequent discussion:

<u>Category I</u> - safety related structures, systems, and equipment designed to withstand the effects of the Safe Shutdown Earthquake (SSE) and remain functional (same as NRC Regulatory Guide 1.29 Seismic Category I).

<u>Category II</u> - structures, systems, and equipment necessary to power plant continued operation following earthquakes up to and including the Operating Basis Earthquake (OBE); the OBE is typically one-half of the SSE's peak ground acceleration.

<u>Category III</u> - all items not in I or II above; these items should be designed such that their failure will not impair the functioning of Category I and II equipment.

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*For example, using test data to show that containment plus soil-structure damping values are significantly higher than used in the original design analysis. This is frequently the case and would reduce floor response spectra significantly, say 20 percent, although such reductions change with frequency.

The fraction of OBE response selected for testing should be plant specific. Plant sites with low OBE levels (e.g., 10 percent g or less, zero period acceleration) would presumably tolerate larger fractions of OBE excitation without concern for Category III equipment than sites with larger OBE values. This is postulated for the following reason; fabrication, transportation, and erection/installation loads and static load design margins will generally require strength sufficient to withstand low earthquake excitation. Simple handling will lead to load reversals of 1 g in the earth's gravitational field; transportation and shock in erection might lead to several g's. Thus, reasonableness arguments would seem sufficient for justifying a significant fraction (say up to 100 percent) of OBE loading at low OBE sites without undue concern for Category III equipment.

Since OBE site motions of 0.1 g can be expected to generate containment floor response spectra with peaks of perhaps 0.5 g or more and a zero period acceleration (ZPA) of perhaps 0.3 g or more, it would seem reasonable to tolerate test response spectra that would correspond to horizontal floor response spectra with at least 0.1 g ZPA. This 0.1 g limit also represents a practical bound on the capability of most currently available sinusoidal test equipment to excite containment structures of all but the smallest of plants.

Note that during sinusoidal tests a greater conservatism must be used than during explosive or other impulsive tests. This occurs because the magnification above base motion in a sinusoidal test is proportional to Q, $Q = 1/2\beta$, where β is the fraction of critical damping of the equipment. However, for earthquake-like quasi-random motion, the magnification relation is somewhere between $\sqrt{Q}$ and Q.[2] This indicates an additional conservative factor of about $Q^{1/4}$. For 3 percent equipment damping, $Q = 16.7$ and $Q^{1/4}$ is about 2.0. This would suggest that ZPA containment motion of about 0.05 g is acceptable for sinusoidal motion if 0.1 g is acceptable for "earthquake"-like motion.

The 0.1 g limit on containment floor response spectra ZPA should provide large margins for Category III equipment. Category I and I equipment are designed to tolerate repeated OBE loadings by regulation since the plant itself is expected to remain operational for events up to and including the OBE. Category I equipment has the most rigorous dynamic design requirement and must perform its safety function during and after the SSE.

Cases may exist where the above conservative limit will not be acceptable since achieving the maximum response possible on the containment building is desirable to demonstrate high energy dissipation. Higher levels will be sought, subject to some protection of Class III components. Since the dynamic requirement for Class III equipment is only that it not fail in such a manner as to effect Category I and II systems, the possible damage from testing is of little safety concern. Rather, the issue may be the cost of repair. This repair issue, however, should not be over-emphasized since (1) damage is unlikely at higher than the 0.1 g ZPA level, and (2) identification of major Category III items and post-test function verification should provide cost-effective means of demonstrating continued Category III function.

The reason damage is considered unlikely until well in excess of the 0.1 g spectra ZPA limit is that the preceeding discussions focused only on horizontal test response; vertical motion has not been considered in either testing or in actual capacity of the Class III equipment. This is because high output (>100,000 lb) test equipment is typically designed for horizontal excitation; vertical excitation in the 100,000 lb class is difficult in the frequency range of interest.

The fabrication/transportation/etc. loads on equipment obviously will have simultaneous horizontal and vertical components, while typical horizontal testing does not contain major vertical components.

Test loads on internal equipment may be applied directly or indirectly. Indirect load application testing by driving the containment building and measuring the internal systems' response should present no safety/functionality/licensing issues for containment response levels less than the OBE condition. The safety assessment of Category I and II internal equipment (piping, motors, etc.) during direct driving requires more attention than is usual for containment driving since it is quite possible to direct drive small diameter piping system beyond the ASME Code allowables with the application of several thousand pounds of force in a snapback test. High response generation makes equipment studies necessary to insure tolerable system response levels.

Appendix A lists and categorizes the major pieces of equipment in a typical PWR nuclear power plant that may have to be reviewed to establish allowable test levels.

5.3 Piping Systems

In the past, tests have typically focused on the containment or on major piping systems (primary, secondary, emergency, etc.), safety related equipment (e.g., diesel generators), control panels, and other equipment. Piping systems and their associated equipment (steam generators, pumps, valves, supports and restraints) have also received major attention. Low level testing (loads of, say, several hundred pounds) has not presented safety concerns for piping systems larger than several inches in diameter. Larger amplitudes (say, 1,000 lb and up) have received careful analysis by the applicable portions of appropriate codes, including for recently designed piping systems, the ASME Boiler and Pressure Vessel Code. These evaluations have consisted of the following steps:

(1) development of a linear elastic finite element model of the piping system;

(2) calculation of response to the planned dynamic test series loads;

(3) calculation of response to the planned dynamic test series loads;

(4) combination of the resulting loads in accordance with ASME Code equations pertinent to the particular system (ASME Class I or Class II); and,

(5) determination of the maximum allowable forcing from several such load cases.

Nuclear power plant piping systems should be restricted to dynamic test loads less than those required to produce the maximum allowable stress (stress intensities) under the OBE loading in the system including existing pressure, thermal, gravity and other appropriate loads. Class II systems have stress limits which are derated to treat fatigue. Testing Class I systems at high amplitudes requires explicit treatment of fatigue. Depressurization of systems during testing allows significant increases in test response amplitude since "pressure stress" is routinely 50 percent of the stress limit in many piping systems of interest.

It is expected that the piping system as well as the containment vessel will not suffer adverse effects if the test response is limited to the low value of 10 percent of the predicted OBE response. However, because of the safety function of the primary coolant piping system and because separate piping tests at higher levels may be performed, additional analysis for and monitoring of acceptable test response levels may be required.

New piping systems are designed according to Section III, Division 1, Subsections NB, NC and ND of the ASME Code. The limits set by the Code on piping response provide upper bounds on allowable test response levels. Only Class I (Subsection NB) and Class 2 (Subsection NC) pipes as defined by the ASME Code are discussed in detail herein. The limits for existing piping which may have been designed using earlier codes, including Section 8 of the American Standards Institute, are calculated in a similar manner as above, but may result in substantially lower allowed test levels as older piping systems were usually designed to less stringent design standards. We assume that any future test would use the current design methods to justify test levels.

Appendix B elaborates on piping stress calculations and monitoring techniques using strain gauges.

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6.0 INSTRUMENTATION AND DATA QUALITY

6.1 Introduction

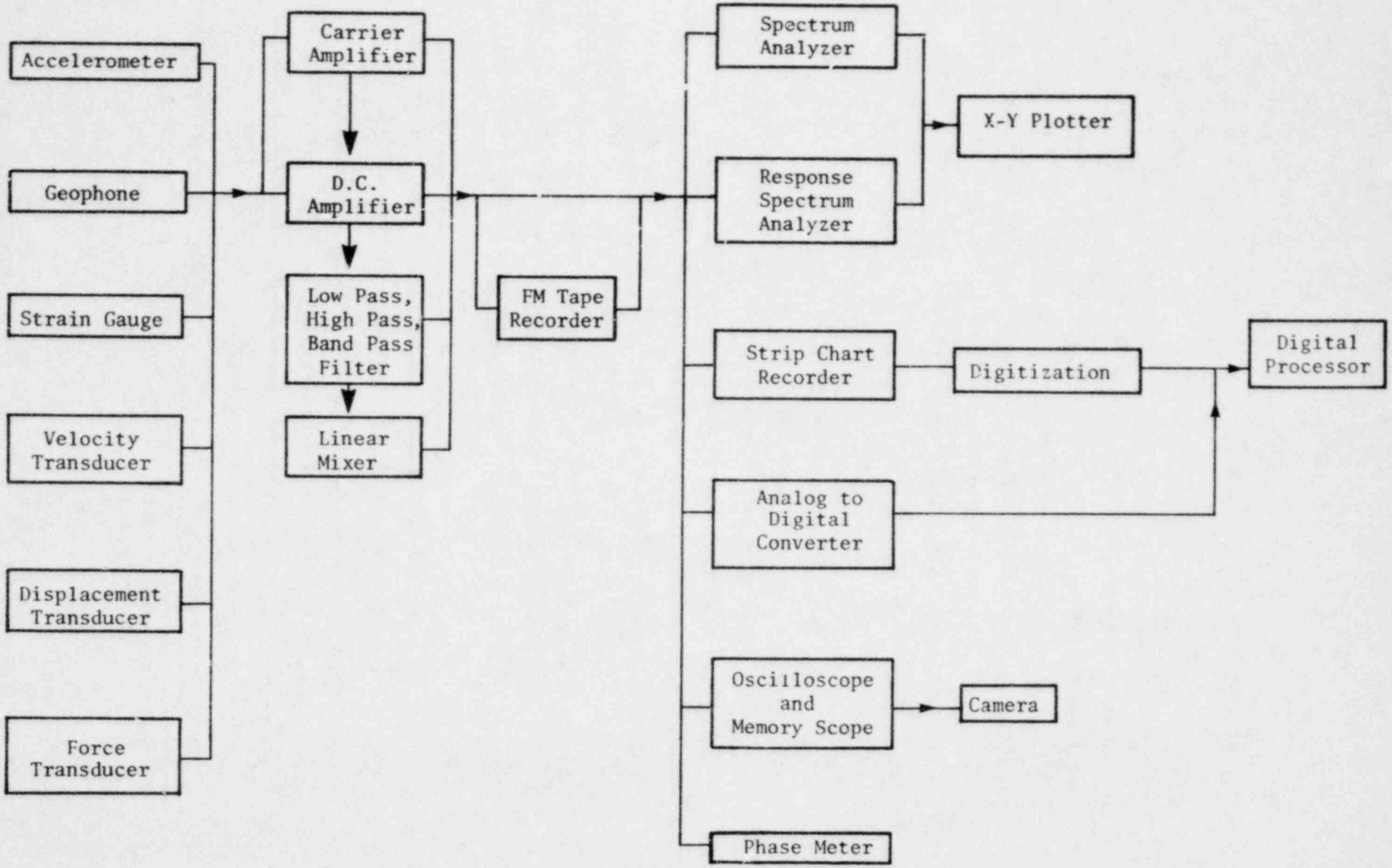
The experimental seismic evaluation of nuclear power plants requires instrumentation which can transduce, record, and analyze strain, relative displacement, velocity, and acceleration. The variety of measurement procedures available is illustrated by the instrumentation block diagram, Figure 6.1. Several types of accelerometers are suitable, including strain-gauge bridge, piezoelectric, piezoresistive, and force balance. Displacement meters usually involve a sliding arm on a variable resistor, or a linear variable differential transformer (LVDT).

A variety of signal conditioning pre-amplifiers, amplifiers, filters, etc., are available. Carrier amplifiers are most often used with strain gauges, strain gauge accelerometers, and strain gauge force transducers. Force balance accelerometers and other transducers are usually processed by DC amplifiers. Filters are useful for eliminating noise, the effect of modes of vibration other than those under study, and for baseline correction. A linear mixer, which adds or subtracts signals in a predetermined manner, is helpful in enhancing the response of one mode above others. The conditioned outputs may be FM tape recorded, analyzed on-line, or digitized on-line. The tape recorded signals may be reproduced and analyzed after the testing.

Many sophisticated devices are used to process the vibration data. General purpose single-channel spectrum analyzers compute PSD on Fourier transformers. Two-channel analyzers compute ordinary and cross spectra, transfer function, and other statistical measures. The resulting spectra and transfer functions may be compared individually with analytic results, or digitized for more extensive computer comparisons.

In addition to general purpose analyzers, several companies have produced minicomputer-based systems for excitation, data acquisition, data

FIGURE 6.1: GENERALIZED BLOCK DIAGRAM OF INSTRUMENTATION FOR SEISMIC EVALUATION OF NUCLEAR POWER PLANTS



reduction, and data analysis. Many of these companies are concerned with ground vibration testing of aerospace structures. Their systems typically drive multiple electrodynamic vibrators and process up to several hundred response monitoring channels. The minicomputer can be programmed to perform correlation, calibration, filtering, curve fitting, parameter identification, force appropriation, spectral analysis, orthogonality checks, transfer function computation, graphics, and report generation. Several companies have commercial systems available with similar capacities.[10]

6.2 Instrumentation Requirements

For all instrumentation, the frequency range of interest is usually between 0.5 and 30.0 Hz, with most structural modes of interest below 10.0 Hz. The acceleration levels to be measured range from 0.001 to 1.0 g. Strain levels range from 1 to 1,000 μ in./in.

More specific requirements are associated with two objectives: first to insure the structural safety of the facility during testing and second, to describe the dynamic response with measured quantities suitable for comparison with analyses and for use in parameter identification.

The objective of structural safety monitoring is to indicate and/or prevent strain or acceleration level exceedences at critical locations. For this purpose, threshold sensing instrumentation systems may be utilized instead of continuous recording and analysis. The fixed systems specified in ANSI N18.5-1974 [1] for earthquake response monitoring are suitable, in principle, for safety monitoring during vibration testing. Note that existing systems are attractive cost-wise. However, their use is not encouraged except as back-up because of limited coverage and non-uniformities in instruments and locations. In addition, the thresholds may be higher than desired for testing at vibration levels below OBE levels.

The instrument performance parameters which must be reconciled with test objectives are frequency response, threshold level, dynamic range, and sensitivity. In addition, size, ease of installation, fragility, and cost are considerations in instrument selection. Finally, the total number of desired measurements may be made simultaneously or by moving transducers and repeating test conditions. Therefore, instrumentation costs may be traded off against testing costs.

6.3 State-of-the-Art

The principles of operation of data acquisition and analysis equipment are discussed in books and special studies.[2,3,4,5] These references in turn draw upon numerous publications covering special operational aspects and error sources. Instead of reviewing and abstracting these references, this section will be limited to identifying the important characteristics of commercially available components.

A variety of transducers, amplifiers, and recording and analysis instruments are suitable. Many such units have been developed primarily for other than seismic applications, but are useful because their performance matches measurement requirements. Of these devices, accelerometers, amplifiers, spectrum analyzers, and modal analysis systems are discussed herein.

6.3.1 Accelerometers

Accelerometers all function in essentially the same manner. The relative motion between the test object and an inertial mass within the accelerometers is sensed with an electrical pick-off device. The type of pick-off device identifies the type of accelerometers. Four different types of suitable accelerometers are as follows:

- wire strain gauge;
- servo or force balance;
- piezoelectric, self-amplified; and,
- piezoelectric, non-amplified.

The wire strain gauge and servo types incorporate 0.7 critical damping and are useful up to approximately 70 percent of the natural frequency. Piezoelectric types have little inherent damping and are used to approximately 20 percent of the natural frequency. Note that servo-type accelerometers are closed loop devices in which the relative motion between case and inertial mass is sensed and an approximate restoring force applied through a coil. The restoring current is proportional to the applied acceleration. The specification performance characteristics of candidate models of all four types of accelerometers are presented in Table 6.1. Important features to consider in accelerometer selection are high sensitivity, low output impedance, low cross-axis sensitivity, and ruggedness.

6.3.2 Amplifiers

Typical medium to high gain amplifiers are listed in Table 6.2. Important features for vibration response measurement are low pass filtering and DC offset adjustment.

6.3.3 General Purpose Spectrum Analyzers

The characteristics of 17 general purpose spectrum analyzers are listed in Table 6.3. The units are all capable of working in real time with no loss of data. The two-channel units are decidedly more useful because they can compute the response at a point which is due only to an input signal. This effectively improves the signal-to-noise ratio.

Otherwise, the most important features are cost, ease of operation, and identification of ranges and calibrations.

6.3.4 Computerized Modal Analysis Systems

Table 6.4 summarizes several commercial and institutional computerized vibration and modal analysis systems. These systems can digitize and document data *in-situ* and greatly reduce subsequent data handling. In this capacity they have already proven themselves in many vibration tests. The modal

TABLE 6.1: SPECIFICATION PERFORMANCE CHARACTERISTICS OF LOW FREQUENCY, HIGH SENSITIVITY ACCELEROMETERS

Type	Manufacturer	Model No.	Mass gm	Excitation		Output Ω	Freq. Resp. Hz		Sens v/g	Range		Noise Floor	Threshold/ Hysteresis	Shock	Cost $	Cross Axis Sens.,
				volts	ma		±5%	±3		±g	±v	g^2/Hz dB	g x 10^{-5}			
Wire Strain Gauge	Statham	A3-1.5-350	390	11	31	350	0-30	0-50	0.03	1.5	0.044	(-93)*	not spec.	not spec.		2
Servo or Force Balance	Sundstrand	QA1100-AA01-17	80	±15	15+	3800	0-300	not spec.	5	2.50	12.5	-98 (-90 → -105)	0.1 → 0.3	250g 11ms	950	0.2
	Kistler	303T13	100	28	<40	100	0-330	0-500	2.5	2.0	5	-100 → -106	50	100g 5ms	965	0.2
	Kinemetrics	FBA-1	1300	±12	not spec.	not spec.	not spec.	0-50	1.25	2.0	2.5	-120	not spec.	not spec.	475	3
	Setra	114	44	6	<30	400	0-100 1%	not spec.	0.6	2.5	1.5	-70	250	"Rugged"	575	1
Piezoelectric Amplified	Endevco	5241	170	30	2	50	0.2-2K (±10%)	0.07-4000	0.79	14.1	11.1	-110 (-100 → -110)	~0.3	1000g	375	17
	BBN	510	485	12-30	0.5-5	1800	0.1-150	0.03-250	8	0.25	2	-106	~0.5	10g "Fragile"	700	3
Piezoelectric Nonamplified	Wilcoxon	1001	540	-	-	10^5pf	250	400	1.5	15	22.5	not spec	0.2	not spec.	350	3
Angular Servo	Systron Donner	4590	1400	±15	20	not spec	0-20	0-30	$\frac{50v}{r/s^2}$	0.1- $\frac{rad}{sec^2}$	5	0.07% F.S.	5×10^{-5} $\frac{rad}{sec^2}$	100g 11ms	3000	-

*Test results in parentheses.

TABLE 6.2: AMPLIFIER SPECIFICATION PARAMETERS

Mfg.	Type-Model No.	Input Impedance	Range	Maximum Output, Volts	Frequency Range, Hz	Cutoff Frequency, Hz	Roloff dB/oct	Cost $	
								Amp	Rack
Neff	DC-128	10 M Ω 1000 pf	0.2-2500	±10	0-20K	10, 100, 1K, 10K	12	540	280
Honeywell	DC-122-2	15 M Ω 100 pf	0.2-5000	±10	0-100K	10, 100, 1K, 10K		785	490
CEC	DC-1-182	1 M Ω 50 pf	0.2-200	±10	0-30K	1, 3, 10, 30, 100, 300	12	550	500
Sund-strand	DC with power supply-517	N/S	0.01-10,000	± 1	0-500	10	18	965	320
Ectron	DC-560-C-L	20 M Ω 100 pf	1.0-2500	±10	0.20K (for X1000 gain	10, 100, 1K, 10K	12	350	500
Hewlett-Packard	Carrier-8805A	10 K Ω	50-10,000	±2.5	0-50	-	-	900	~1000/Chan
	DC-8002A	180 K Ω	0.1-100	±2.5	0-50	-	-	500	"
	DC-8003A	1 M Ω	0.2-10,000	±2.5	0-50	-	-	1000	"

TABLE 6.3: GENERAL PURPOSE SPECTRUM ANALYZERS SUITABLE FOR NUCLEAR POWER VIBRATION TESTING

	# Ch	# Lines	Screen Alfa Data	Freq Limits	Weight (kg)	Operations	Comp Inter-Face Avail.	Comments & other Features	Approx. Cost $K
1. General Radio 2512 Spectrum Analyzer	1	400	YES	DC to 10 Hz DC to 10^5 Hz	20	(FFT) AVE HAN	NO		
2. Norland 2001 A	4	512	YES	DC to 2 Hz DC to 10^5 Hz	>80	+, -, ÷, j, AVE v, SIN, COS, TAN, FFT, PSD HAN	YES	Versatile Programable	12-18
3. Princeton Applied Research 4512	1	512	NO	DC to 10 Hz, DC 40×10^3 Hz	15	HAN, FFT	NO	Fast	7
4. B&K 2031	1	400	YES	(?)	~15	HAN (FFT)	NO	1/3 Octave	
5. Nicolet 444A Nicolet 660	1	400	YES	DC to 1 Hz DC to 10^5 Hz	19	TF (FFT) AVE PEAK	YES	2 Memories	10 25
8. Rockland FF 512/s	1 2	400 400	YES	DC to 20 Hz DC to 10^5 Hz	25	AVE PEAK	YES	2 Memories	
9. Singer MF-2, MF-5	1	?	YES	DC to20Hz DC to27.5 $\times 10^6$ Hz	20	(FFT)	NO		
10. UNIGON 1024-A	2	512	NO	DC to10Hz DC to 50 $\times 10^3$ Hz	30	FFT, IFT Auto Spec TF TF COH AVE	NO		
11. SDC SD 340	1	400	NO	DC to 25 DC to 10^3 Hz	15	(FFT)	YES		6
12. SDC SD 360	2	1024	NO	DC to10Hz DC to150 $\times 10^3$ Hz	45	FFT TF ACOR COR CONV. HIST PROB	YES	~26	~40
13. Schlumberger 1510	1	256	YES	DC to 25 DC to 25 $\times 10^3$ Hz	30	AVE (FFT)	?		9
14. HP 3582 A	2	256	YES	DC to1Hz DC to 25 $\times 10^3$ Hz	25	FFT TF COH ZOOM HAN AVE	YES	Built in white noise source	12
15. HP 5420 A	2	Variable and Large Expandable	YES	DCto.016 Hz DCto 25 $\times 10^3$ Hz	52	POLAR FFT COH ZOOM HAN AVE + - x ÷ TIME AVE HIST	YES	Data Storage Tape	~40
16. Time Data TD A31	2	512	NO	DC to ? DC to 10^5 Hz	>100	FFT IFT AUTO CROSS HIST	YES	Program. General Purpose Computer	~50

COMPUTERIZED MODAL ANALYSIS SYSTEMS TABLE 6.4

VENDOR	ANALYSER	FREQ. RANGE	PID SOFTWARE	GENERAL PURPOSE COMPUTER ?	FORCING	REFERENCE
NICOLET OF-400B-MA (411B)	411B	DC to 10^5 Hz	NO	NO	Transient	Product Literature
HEWLETT-PACKARD 5451B (402)	5451B	Up to 50 x 10^3 Hz	YES	YES	Random, Sine Transient	SAE Paper 760875 "Identifying Mod of Large Structures, Multiple Input& Response Measurements" M.Richardson & J. Kniken, NOV 1976.
Spectral Dynamics 2001 DM	SD 360	Up to 150 x 10^3 Hz	YES	YES	Random, Sine Transient	Product Literature
Time Data	----	?	YES	YES	Transient, Random	SAE Paper 751067 "Modal Survey Tech niques & Theory" E.Sloane & Bruce McKeener, Nov. 1975
ZONIC/ Structural Dynamics Research Corp. DMS/TSA	----	?	YES	Yes (Remote)	Transient, Random Sine	SAE Paper 760877 "Modal Analysis wi the DMS/TSA System" D. Durham, and Richard H. Russell
LOCKHEED	MODALAB	?	YES	YES	SINUSOIDAL (up to 16)	SAE Paper 760872 "An Evaluation of Excitation and Analysis Methods for Modal Testing" G.Hamma, Nov. 1976
JPL	-----	---	YES	YES	SINUSOIDAL Random (up to 10)	SAE Paper 760879 "Comparison of Modal Test Results:Multi-Point Sinc versus Single Point Random" Heppert et. al, Nov 1976
TRW	COMCAS	---	YES	YES	SINUSOIDAL (up to 4)	SALYER, R. "Computer Oriented Modal Control and Appraisal System (COM CAS)" IBM 1970 Customer Executive Conf. Report by TRW Systems Jnc Redondo Beach, Calif.

TABLE 6.4 (continued)

VENDOR	ANALYSER	FREQ. RANGE	P ID SOFTWARE	GENERAL PURPOSE COMPUTER ?	FORCING	REFERENCE
HUGHES	MODAPS	---	YES	YES	Sinusoidal (up to 3)	SAE Paper 751069"Space Vehicle Experimental Refinition Using Tra fer Function Techniques" Knauer e al., Nov 1975
ANCO	KOVAS	0 - 500 Hz	YES	YES	Sinsoidal, Transient (up to 8)	ANCO Software Users Guide

analysis and parameter identification aspects have been demonstrated on a variety of structures, notably aerospace structures, but have not been extensively used in nuclear power plants. In any case the use of such systems should be strongly considered in containment or component test programs.

6.4 Instrumentation System Errors

When analysis is verified by experimentation, care must be exercised to insure that the experimental results are more accurate than the analytical results. In order to establish that this is the case, both experimental and analytic accuracies must be estimated. This can be at least as difficult as the basic analysis or experiment. Fortunately, some dynamic parameters are clearly more accurately (or precisely) determined by analysis and some by experiment as outlined in Table 6.5, which presents ANCO's opinion on these matters.

Experimental error is not a serious concern for those cases where reasonable accuracies can produce results which are much more accurate than analysis. Instrumentation errors, for example, have a significant effect on mode shape and frequency response function determination, but not so much an effect on resonant frequencies.

Errors also may be broadly classed as being either bias errors or random errors (see Figure 6.2). Bias errors are those which have a constant or systematic effect on measurement. Random errors are those which can cause variations in data than can only be predicted on the basis of probability. Thus, the instantaneous voltage of a data signal which includes extraneous noise will have a random error tending either to increase or decrease the voltage. Each of the boxes in Figure 6.2 has to be considered when analyzing the errors in any given test program.

The measurements taken in a typical test program consist largely of accelerations and displacements measured with transducers. These transducers are calibrated on a regular basis to an accuracy of about ±8 percent

TABLE 6.5: RELATIVE ACCURACY OF ANALYSIS AND EXPERIMENT IN DETERMINATION OF DYNAMIC PARAMETERS

Dynamic Parameter	Analysis*	Experiment*
Structural Mass	H	M
Structural Stiffness	M	M
Effect of Soil Dynamics	L	M
Structural Damping	L	H
Natural Frequencies:		
Low Mode Order	M	H
High Mode Order	M	M
Mode Shapes:		
Low Mode Order	M	H
High Mode Order	M	M
Frequency Response Functions	M	H
Response to an Earthquake	H	M

*H = high accuracy
M = moderate accuracy
L = low accuracy

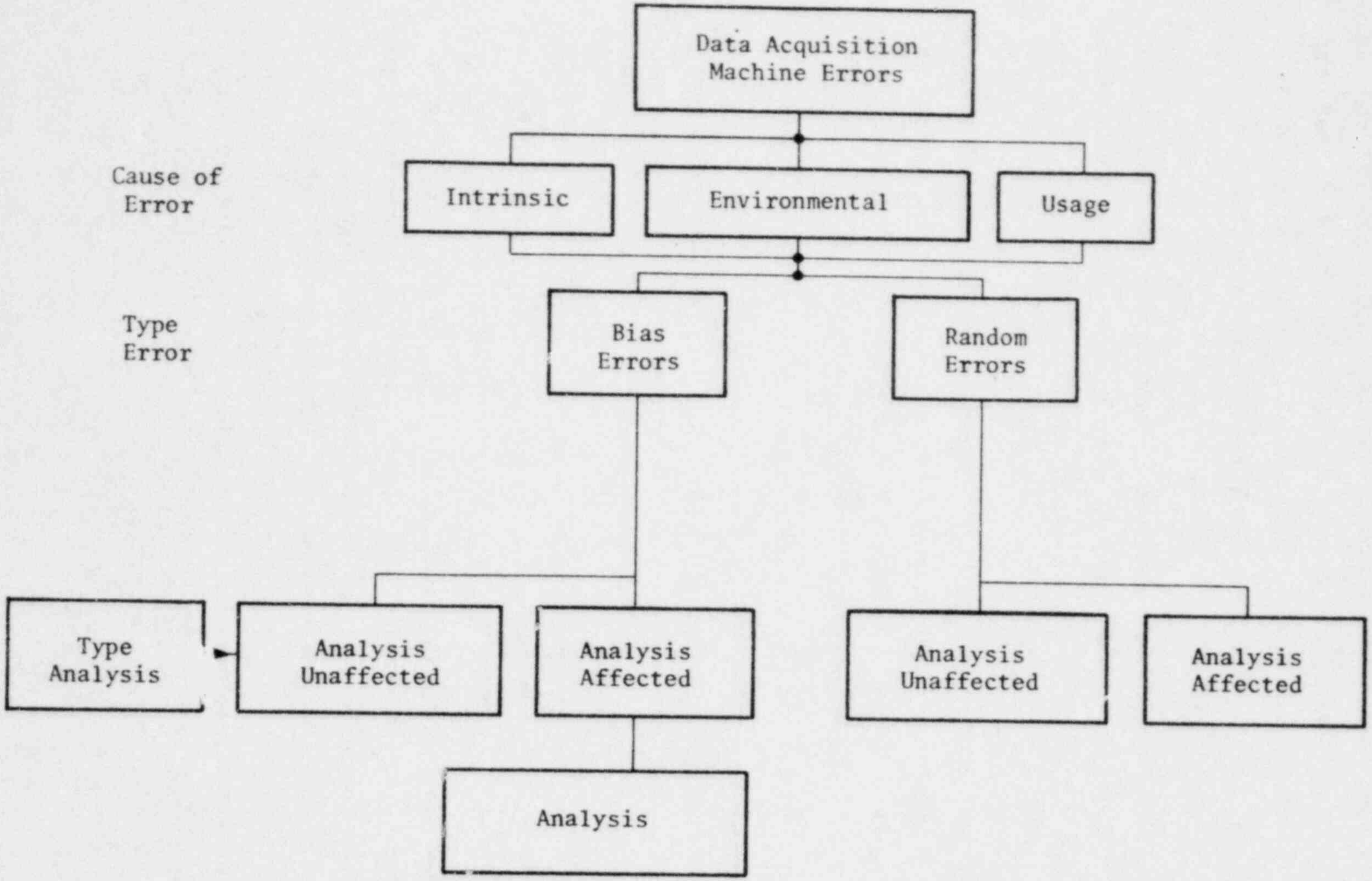


FIGURE 6.2: CLASSIFICATION OF MACHINE ERRORS
DEPENDING ON TYPE ANALYSIS

(reference signal error 1 percent, calibration read error 2 percent, daily drift 2 percent, and amplifier linearity 3 percent). Combined with an additional 2 percent transducer placement error and a 2 percent data read error, this indicates that acceleration and displacement values are accurate to about ±12 percent. Relative errors using the same transducer in the same location, however, are smaller, i.e., about ±7 percent.

These data are then processed either by hand or other instruments to produce graphical results. The error added in this process is variable and difficult to specify but is probably on the order of ±5 percent. (For the sake of discussion, this is called "plotting error.")

Note that the errors involved here are random and would tend to cancel somewhat and reduce the overall uncertainty. Also, the errors quoted are for worst case situations. Most data are more easily interpreted and probably involve errors about one-third of those quoted above.

Graphical data are used to estimate parameters such as resonant frequencies and dampings. Note that in most cases these estimates are unaffected by the transducer error (±12 percent) as dimensionless techniques are used to obtain the estimates. Also the "plotting" error does not necessarily affect the estimate in a proportional way.

In fact, with good experimental practice the dominant source of error in estimates of frequency and damping comes from nonlinear structural response. Consider that "resonant frequency " "(viscous) damping," "log decrement," and "half-power bandwidth" are linear concepts being used to describe somewhat nonlinear structures. Thus, at the same level of response sinusoidal excitation will yield different parameter estimates than transient excitation and the log decrement method will yield different values than the half-power bandwidth methods. Further, applying these linear concepts to the nonlinear data requires some interpretation which causes estimates obtained by different engineers to differ somewhat (about ±1 percent for frequency, and ±10 percent for damping).

Experience indicates that "equivalent" resonant frequencies can vary by as much as ±5 percent and "equivalent" dampings by ±20 percent for the same response level, method of testing, and data reduction. Other testing and technique data analysis methods can increase these variations significantly. These effects are separate from the very real and considerable changes that occur in these parameters when excitation or response levels are changed.

Instrumentation random errors and experimental variability contribute to inherent inaccuracies in both modal and frequency response type parameter identification procedures.[6,7,8,9] Fortunately, modal analysis procedures have inherent orthogonality checking features which permit verification of the acceptability of the results. Similarly, frequency response computations have statistical errors which decrease with increasing record length.

In summary, using state-of-the-art methodology, the only instrumentation system errors which are considered serious enough to degrade the results are incorrect bias errors. These include transducer frequency response and calibrator error. However, the most important source of error is human mistakes in transducer orientation and amplifier gain settings. The use of an experienced test team, check lists, and digital data logging helps to reduce this problem.

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7.0 DATA PRESENTATION AND PARAMETER IDENTIFICATION

7.1 Introduction

The objective of the testing itself is to provide response data. These data must be taken and processed in a manner as to be readily used for purposes of test review, safety evaluation, and parameter identification.

7.2 Data Presentation

ANCO's experience indicates that, preferably, the data are taken *in-situ* in digital form; FM tape recorders may serve as a temporary storage medium. Early in the test period or during early steps of the post-analysis, the data must be converted to engineering units, baseline corrected, filtered, and documented. Any processing done must be clearly indicated. Eventually all data should be put into digital form and 10-20 percent of the data presented graphically. The data should be set up in standardized fixed field format files in a universally accepted digital format and medium (e.g., ASCI magnetic tapes).

7.3 Parameter Identification

Some parameter identification can be performed *in-situ*. Aerospace testing has long used multiple shakers to "tune" pure modal response and, therefore, identify modal properties on a mode-by-mode basis. Use of multiple forces to test a containment would be difficult; hence, this method is not appropriate for nuclear power plants (except, perhaps, for components). Other *in-situ* parameter identification techniques depend on rapidly processing data obtained from single point excitation. These techniques have never been used in containment studies and their applicability and relevance is not established. Most likely only preliminary simple parameter identification need be performed in the field. Subsequent parameter identification on the acquired data base would be conducted in the post-analysis.

Parameter identification techniques have been reviewed by Ibáñez.[1] There exist many methods: simple and complex, proven and unproven, with greater or lesser applicability to nuclear power plant containments and components. These techniques can be divided into two groups: (1) those techniques (eigenparameter identification) which can be used to estimate resonant frequencies, damping, and mode shapes from experimental data; and (2) those techniques (model modification) which can be used to modify the mass and stiffness properties of structural models given the experimental estimates.

7.4 Eigenparameter Identification

Eigenparameter identification techniques typically use a linear combination of single-degree-of-freedom response curves to fit the data.[1] The parameters such as resonant frequencies and damping are varied to reduce the difference between data and theory and find the "best" parameters. An alternate approach is to do a one-step evaluation of the best parameters using computer codes such as the PARET code developed at Lawrence Livermore Laboratories.[2] These techniques can also be categorized by their operation on data in the time domain or frequency domain (Fourier transform or sinusoidal data). Certain methods have been developed for handling nonlinear model parameter identification,[1] but these have not been extensively used in practice.

7.5 Model Modification and Bayesian Techniques

Once the analyst estimates the eigenparameters, he or she may ask "how should I change my model to more closely reproduce the experimental data?" This can be carried out by simple heuristic "trial and error" methods or by more sophisticated mathematical techniques. Of the latter techniques, the Bayesian identification is particularly powerful.[1]

The objective of Bayesian Parameter Identification (BPI) is to find a set of optimal model parameters which simultaneously minimizes the difference between measured and predicted response and between initial (*a priori*) parameters and final optimal parameters. This dependence on *a priori* parameter estimates is justified on two grounds. First, experimental data often do not uniquely define the model parameters and additional constraints are required to choose a unique set. Second, it is assumed that the analyst's *a priori* choice of model parameters is a reasonable one based on his or her judgment, previous results, and preliminary data. Consequently, it is reasonable to introduce additional constraints by choosing the set of optimal parameters that differs in some least way from the initial estimates. These minimum criteria are least square in nature and are weighted to allow the more certain data and more certain initial parameters to control the optimal parameter selection to a greater extent than the less certain data and the less certain initial parameters.

Consider the example of a single-degree-of-freedom oscillator. The analyst has estimated its mass at 1.0 kg with an uncertainty of ±0.32 kg. The stiffness has been estimated at 1.0 N/M ± 0.55 N/M. The predicted resonant frequency is 1.0 radian/second, but is measured at 0.9 radian/second with experimental error of ±0.22 radian/second. What is the best estimate of mass and stiffness based upon these data? Clearly the problem is undetermined. A stiffness of 0.81 and mass 1.00 is a solution. A stiffness of 1.0 and mass 1.23 is a solution. For that matter a stiffness of 100.0 and a mass of 123.0 is a solution. The latter case is unreasonable based on the analyst's estimates. No cases account for the possible error in the data.

The BPI technique seeks to introduce uniqueness and account for *a priori* estimate error and data error by minimizing the mean square error $E(m_o,k_o)$ where:

$$E(m_o,k_o) \equiv \frac{(k - k_o)^2}{\sigma_k^2} + \frac{(m - m_o)^2}{\sigma_m^2} + \frac{(w_o - w_m)^2}{\sigma_w^2}$$

where

m = *a priori* mass estimate;

k = *a priori stiffness estimate;*

m_o = optimal value of mass;

k_o = optimal value of stiffness;

w_m = measured value of resonant frequency;

w_o = optimal value of resonant frequency corresponding to m_o and k_o;

σ_k = uncertainty in *a priori* stiffness estimate;

σ_m = uncertainty in *a priori* mass estimate; and,

σ_w = uncertainty in measured resonant frequency.

The model parameters, m_o and k_o, are related to the measured parameters, w_o through the relation:

$$w_o = \sqrt{\frac{k_o}{m_o}} .$$

Therefore,

$$E(m_o,k_o) = \frac{(k - k_o)^2}{\sigma_k^2} + \frac{(m - m_o)^2}{\sigma_m^2} + \frac{\left(\sqrt{\frac{k_o}{m_o}} - w_m\right)^2}{\sigma_w^2}$$

This error function can be minimized either by setting its partial derivatives with respect to m_o and k_o to zero and solving the resulting nonlinear equations, or by numerical techniques. In either case the solution is:

Parameter	*A Priori* or Measured Value	Optimal Value	% Difference
Mass	1.00 ± 0.32	1.030	3.0
Stiffness	1.00 ± 0.55	0.895	11.0
Resonant Frequency	0.90 ± 0.22	0.932	3.6

As can be seen, a "happy medium" has been found--changing the stiffness more than the mass (as its uncertainty was greater) and matching the resonant frequency closer than the average of the model parameter changes (as its uncertainty was least).

This technique can be generalized to treat any number of measured and model parameters. Linearization of the criteria function yields a particularly simple algorithm.

7.6 Conclusions

Some parameter identification must be carried out in the field. This would include graphic presentation of sinusoidal or Fourier transform data to provide rough estimates of resonant frequencies and damping and the plotting of response shapes at resonant frequencies to yield a rough estimate of mode shapes.

Subsequent eigenparameter identification should use least-mean square type modal fitting routines or one step routines should they prove suitable with typical data (the least-mean square techniques have been proven out in a variety of cases). The objective of this stage is to estimate resonant frequencies, damping, and mode shapes.

The final step of the identification should consist of Bayesian identification of important structural parameters and soil properties. The Bayesian technique can also work with nonlinear model properties.

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8.0 TESTS ON INTERNAL COMPONENTS

During testing of the containment, or as separate tests, data may be gathered on the dynamics of building internals, such as piping and components. It may be possible to "piggyback" tests on components during shaking of the containment. There are certain advantages to this approach:

- If containment tests are being performed anyway, the excitation is "free."
- The excitation enters the equipment from the base, as does an earthquake, and this may be an advantage for heavy equipment or in structures in which base motion is important (e.g., fluid filled tanks).
- The base excitation will emphasize those modes of vibration important to earthquake response.
- All plant equipment is excited at the same time and this may be important for cases in which equipment to equipment interaction is important.

There are also certain disadvantages to this approach:

- High levels of response may not be feasible.
- The dominant input will be at the resonant frequencies of the containment rather than at the resonant frequencies of the equipment. The input is difficult if not impossible to control.
- All equipment is excited; it is not possible to isolate and test just one component.

It is not reasonable to test equipment by containment excitation if the only objective is the equipment tests. Direct excitation of the equipment is easier and less expensive. If the containment is being tested in its own right, however, a reasonable amount of equipment testing can be "piggyback."

The techniques used for testing equipment directly are very similar to those used for containment testing. These have been reviewed in detail in reference [1]. Testing of a complex piece of equipment or piping system can approach the complexity and cost of a containment building test. Many simpler pieces of equipment or tests with limited goals nevertheless can be performed for more modest costs, as discussed elsewhere in this report.

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9.0 EXTRAPOLATION OF DAMPING AT HIGHER RESPONSE LEVELS

9.1 Containment Structures

The damping of a reactor building during dynamic loading is associated primarily with two mechanisms:

(1) structural deformation; and,

(2) soil-structure interaction with energy being absorbed by the surrounding soil media by hysteresis and with radiation of energy away from the oscillating structure.

Damping data obtained from full-scale tests and model tests (see Section 3.0) are summarized in Table 9.1. The total damping is reported; the separate effects of structural deformation and soil-structure interaction have not been obtained.

Forced sinusoidal vibration tests with 70,000 lb force of the Tokai-2 containment building resulted in a peak acceleration of one milligee on the operating floor 125 ft above the ground. The estimated damping of the first (rocking-translation) mode was 15 to 20 percent.* Damping in the higher modes was estimated to be 8 to 15 percent with the lower damping values corresponding more to structural deformation than to soil-structure interaction. Soil-structure interaction is manifested primarily in the lower modes of vibration.

The EGCR (a steel containment in a stiff soil with shear wave velocity V_s = 4,000 ft/sec) and the CVTR (a concrete containment in a softer soil) were both tested at one milligee response amplitude. The estimated damping for the EGCR was 2 to 3 percent and the estimated damping for the CVTR was 6 percent. These data, and other test data, suggest that concrete containments at soft sites are characterized by higher damping than steel containments at stiff sites. Higher level tests [1] suggest that a damping value of 15 to 20 percent is representative of concrete containments and soft sites.

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*Personal communication between George E. Howard, ANCO Engineers, Inc., and various Japanese investigators.

TABLE 9.1: SUMMARY OF MEASURED DAMPING

Nuclear Plants	Estimated Damping
SONGS-I* (San Onofre, California)	16 to 18% in forced vibration testing, 20% in low level earthquake
EGCR* (Oak Ridge, Tennessee)	2 to 3% at one milligee, forced vibration testing; 3 to 4 percent at 10 milligees, blast testing
CVTR* (Pass, South Carolina)	6% at one milligee, forced vibration testing
Enrico Fermi* (Monroe, Michigan)	6% at 10 milligees, blast testing
Tokai-2[3] (Japan)	15% or higher in fundamental mode at one milligee, higher modes involving concrete deformation were 8 to 15%, forced vibration testing
Hamaoka[3] (Japan)	15 to 23%, forced vibration testing
Model	
EPRI Model Experiments,* (New Mexico)	15 to 20%, at scaled accelerations of 0.1 to 0.5 g, forced vibration and blast testing

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*ANCO tests, references [1] and [2].

Test results suggest that the damping increases with increasing response amplitude. The San Onofre Nuclear Generating Station (SONGS) was tested using eccentric shakers for forced vibration with sinusoidal force output of approximately 10,000 lb. This resulted in an amplitude response of one milligee and an estimated 16 to 18 percent damping.[1] These damping estimates compare to an estimated damping of 20 percent obtained from instrument monitoring during a low level earthquake which resulted in a response amplitude of approximately 10 milligees. Forced vibration testing of the EGCR resulted in response amplitudes of one milligee and a damping of 2 to 3 percent. Blast testing resulted in response amplitudes of 10 milligees and a damping of 3 to 4 percent.

Increased damping with increased response amplitude has been observed in other full-scale tests [1] and in model tests.[2] However, the relationship between the response amplitude and damping is nonlinear and extrapolation of damping at higher response levels would require several intermediate level tests.

For example, the SONGS and the EGCR containment vessels have been tested and the damping ratios estimated at one milligee and at 10 milligees response levels. Further tests between 10 and 100 milligee levels would allow a polynomial curve to be fitted between the damping ratio β and the peak response S_a. That is,

$$\beta = CS_a^n$$

where C and n are constants determined from a least squares fit. This functional relationship between the damping ratio and the peak response could then be used to extrapolate the damping ratios at even higher response levels which are typical of earthquakes. The reliability of the extrapolation would increase as further seismic tests at varying levels and on varying structures at varying sites were performed.

9.2 Internal Equipment

Considerably more data are available on equipment damping and have been summarized in references [3] and [4]. As indicated in the following two case studies, taken from [4], damping is generally higher than allowed regulatory values at reasonable test levels and increases with increasing response. (Some damping measurements at Diablo Canyon [5] on a 5 in. pipe indicated a high damping of 16 percent at 0.01 g, lower damping of 5 percent at about 0.50 g, and slowly increasing damping above 0.50 g [up to the test limit of 1.0 g]. This odd trend is believed due to Coulomb damping in gaps which is more effective at lower levels of response.)

DAMPING CASE STUDY #1

DAMPING MEASUREMENT ON A PRESSURE VESSEL MODEL

In order to begin to study the dependence of damping upon response amplitude for nuclear reactor equipment response, a one-fifth scale model of a typical reactor component was built. The amplitude of the initial displacement was varied and damping estimated from measured free vibration traces.

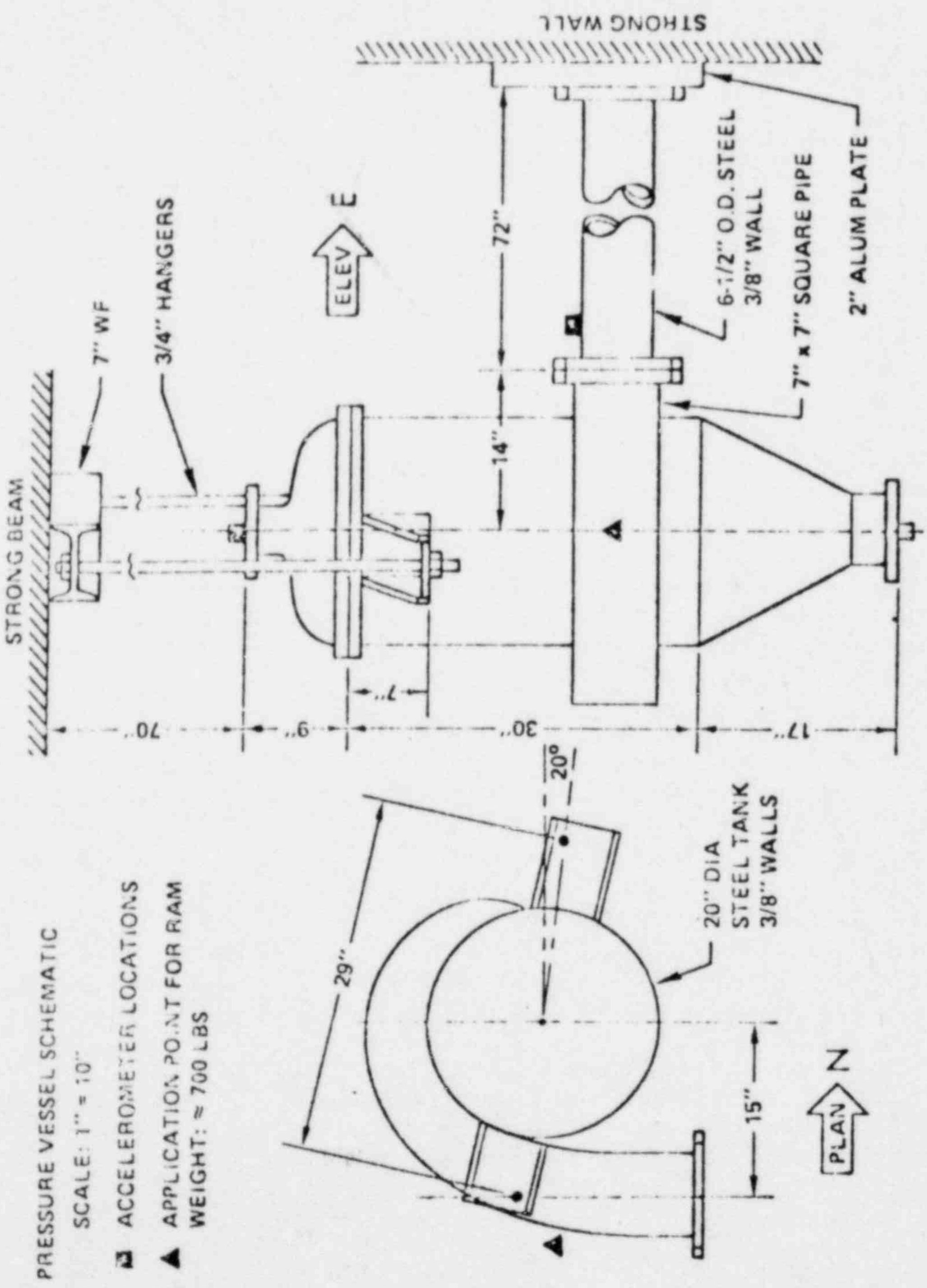
The model is shown on the next page. This figure shows a steel pipe rigidly bolted to a strong wall at one end and to a steel vessel at the other. The steel vessel, roughly cylindrical in shape, and weighing approximately 700 lbs. is bolted to the free end of the pipe, and suspended by two steel rods from the ceiling. The hangers stiffen the system in the vertical direction so that the motion is in the horizontal plane.

The system was excited in free vibration using two techniques. At low acceleration levels, less than 1 g, the system was manually displaced and records of transient motion were recorded. In order to attain higher acceleration levels a piece of timber was placed against the side of the vessel and a hydraulic ram was placed between the other end of the timber and a solid wall. After the desired initial displacement was achieved the vessel was released to freely vibrate by striking the timber with a hammer.

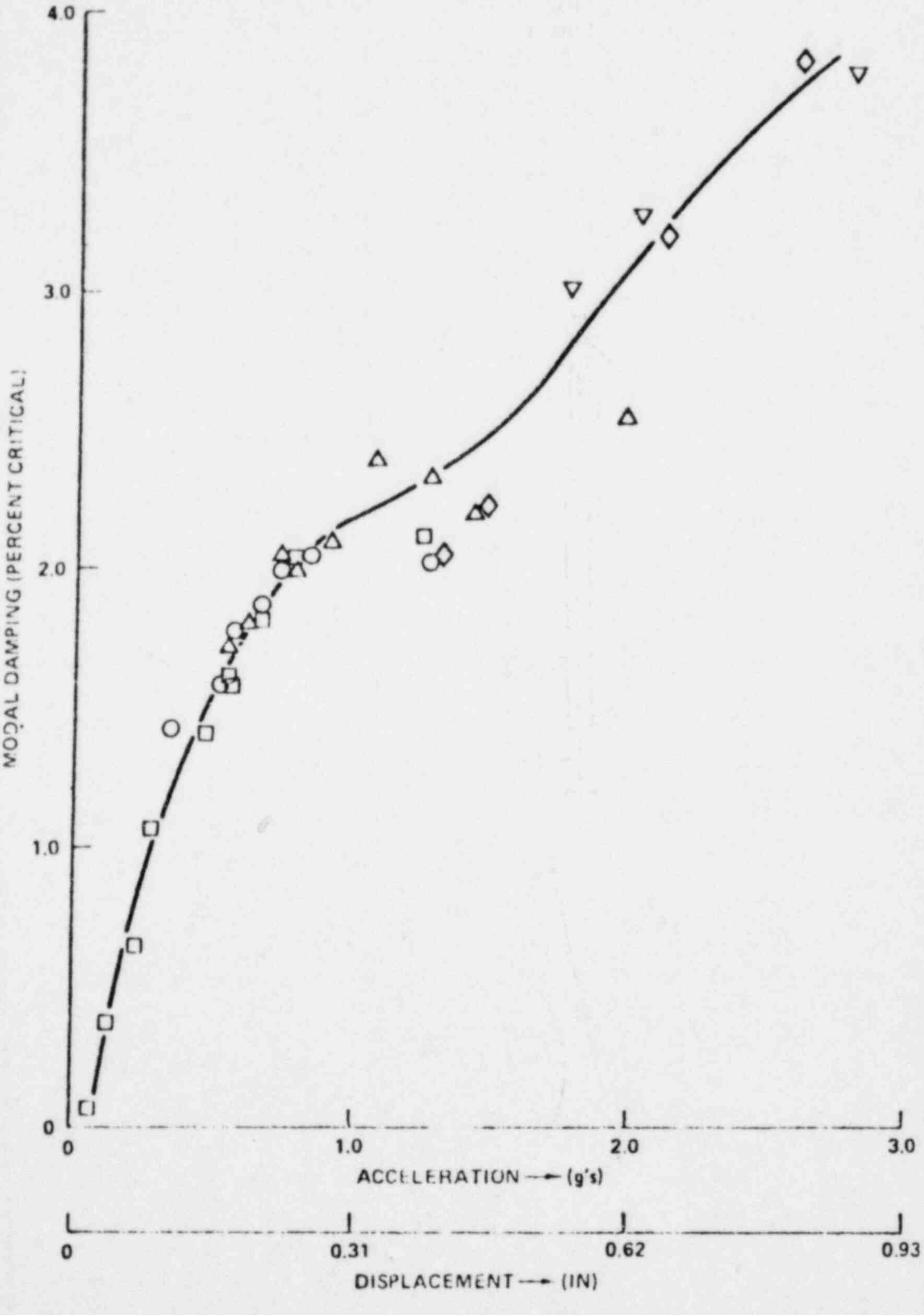
First, the vessel and the pipe were unbolted and separate free vibration tests were conducted on each element. The pipe in its cantilever position possessed a natural frequency of 29.8 Hz. Damping of the pipe alone was 0.34 percent critical at .16 g. The natural frequency for the pendulum type oscillations of the vessel in its uncoupled position was 0.53 Hz. This value for the natural frequency was invariant under all initial displacements used in the tests. The coupled system resonant frequency was 6.1 Hz.

Damping was obtained from the acceleration records using the logarithmic decrement method. It was found that five cycles of motion were necessary to minimize scatter in the damping estimates and therefore the damping values were obtained using the logarithmic decay experienced over a time span corresponding to five periods of vibration.

The graphical results show the estimated damping plotted versus response amplitude. The plot shows an essentially linear increase in damping magnitude with amplitude. It is believed that the structure experienced some yielding when the initial static displacement was greater than approximately 1.0 - 1.25 inches. The scatter in the damping values in this range seems to indicate such a system change.



Plan and Elevation of Laboratory Test Structure



Damping Versus Response Amplitude

DAMPING CASE STUDY #2

DAMPING ESTIMATES ON PRESSURE VESSEL SYSTEMS

Currently the damping values allowed to be used in the dynamic analysis of nuclear power plants are specified by NRC Regulatory Guide 1.61 as shown below. Values are in percentage of critical damping. The Safe Shutdown Earthquake (SSE) is generally taken as the largest that could conceivably occur at the site, while the Operating Base Earthquake, usually half the SSE, is taken as the earthquake likely to occur during the operating life of the plant. The plant must continue to operate without damage after the OBE and shut down safely (although possibly damaged) after the SSE.

Structure or Component	Operating Basis Earthquake or ½ Safe Shutdown Earthquake	Safe Shutdown Earthquake
Equipment and large-diameter piping systems, pipe diameter greater than 12 in.	2	3
Small-diameter piping systems, diameter equal to or less than 12 in.	1	2
Welded steel structures	2	4
Bolted steel structures	4	7
Prestressed concrete structures	2	5
Reinforced concrete structures	4	7

The experimental data on pressure vessel systems indicate that the regulatory values are somewhat low. The table below summarizes many of the experimental damping studies discussed in the text and indicates that the allowable OBE values are equal or exceeded even at low response levels (<0.10 g). As experimental data suggest that damping increases at higher response levels, it would appear that regulatory values are low by a factor of 50 to 100 percent.

Nuclear Power Plant	Component	Response Level (g)	Measured Damping (% of critical)	Applicable Regulatory Value (OBE)
Experimental Gas Cooled Reactor	Steam Generator	0.001 1.0	1.0 2.0-3.0	2.0
	Steam line	0.1	2.0-3.0	1.0
Enrico Fermi I	Intermediate Heat Exchanger	0.001	10.0	2.0
	Secondary Sodium Pump	0.010	3.0	
	Sodium/Water Steam Generator	0.010	10.0	
San Onofre	Pressurizer	0.001 0.10	1.5-2.0 1.5-2.0	2.0
	Primary Coolant Loop	0.01 0.10	1.5 2.0-4.0	
	Reactor Vessel	0.0001	1.5	
Indian Point II	Steam Generator	0.010	2.2-5.0	2.0
	Crossover Leg	0.001	5.0	2.0
	Pump	0.001	1.0-1.3	2.0
Tsuruga	6" to 16" Pipeline	low level	3.2-8.6	2.0
	0.75" to 2.5" Pipeline	low level	0.2-3.4 (avg. 1.4)	1.0
UCLA Laboratory	6" dia Pipe	1.00	4.0	1.0

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10.0 BUDGET AND SCHEDULE FOR TESTING OF A TYPICAL PLANT

10.1 Introduction

The planning of a vibration test on a nuclear power plant consists of the following three tasks: (1) a pre-test analysis; (2) a test plan based on both the stated objectives and the results of the pre-test analysis; and (3) a post-test analysis. Each of these tasks is discussed in the following sections. The test object is a typical PWR and the test objective is to determine the dominant horizontal modes of vibration in both directions and the dynamic properties of selected internal equipment.

10.2 Pre-Test Analysis

The pre-test analysis involves the delineation of an *a priori* analytical model of the reactor containment building (RCB). The fundamental purpose of developing an *a priori* model is to assist in preparation of a detailed test plan. The analysis would aid in determining: (1) the optimum location and the required force output of the structural vibrators necessary to excite the lowest RCB vibrational modes; (2) the required sensitivity of the transducers used to record the dynamic response of the structure; and (3) the optimum location and number of transducers necessary to detect and map the modes of interest.

To accomplish these tasks, it is necessary to predict the expected dynamic behavior of the structure (the natural frequencies, mode shapes, damping ratios, and time and frequency response) via some analytical scheme. The analytical approach requires the development of a finite element model of the structure. The structure would be defined as an assemblage of beam and/or shell elements. The soil medium would be represented as either a continuous medium using two- or three-dimensional solid elements or as single compliance functions using linear springs to account for soil-structure interaction effects.

It is desirable to analyze the RCB as a linear model. The nonlinear response of the soil medium can be mathematically linearized knowing the input force levels and range of expected response. Gaps, banging and other geometric effects are nonlinear phenomena and difficult to linearize, but are found not to have significant effects on the global modes of vibration of containment structures. The advantages of using a linear analytical model are that eigenparameters (frequencies and modes) exist and are easy to calculate. Also, system response is predictable via modal superposition. The eigenparameters can then be directly compared to test results. This containment model is not a complete one as it is intended to yield only an approximate idea of the dynamic properties of the structure.

If it is determined that significant material and/or geometric nonlinearities exist in the structure invalidating linear analysis, then a nonlinear analysis of the structure would be undertaken. The computational time for nonlinear response analysis is typically an order of magnitude greater than the time required for linear response analysis.

The tests are to be done on existing power plants. Therefore, it is possible that dynamic modeling and analysis was done in the seismic design phase of the plant. The results of these analyses would be useful in the formulation of or substitution for the pre-test analysis models. This would greatly reduce the expenditures required to accomplish the *a priori* analysis.

If it is determined that the pre-test analysis could be accomplished via linear techniques, the following steps are necessary to accomplish the analysis:

(1) gathering information on the composition and design of the RCB;

(2) computer modeling of the structure;

(3) eigenvalue extraction; and,

(4) dynamic response analysis to postulated test conditions.

The most suitable methods to excite the containment structure are:

1. (1) harmonic forcing via an eccentric mass vibrator; and,
2. (2) ground motion generated by buried explosive charges.

For this reason the dynamic simulations performed with the model of the containment will be of frequency response for harmonic forcing and time history response for explosively generated ground motion.

These two methods of testing are well established and are the only ones selected for use in defining the test plan. There are other methods which could be used but they have not been used to any practical extent to test nuclear power plant containments.

The discussion of the pre-test analysis of reactor containment buildings applies generally to the analysis of containment internals (i.e., heat exchangers, pumps, and piping systems). The modeling, possible eigenparameter analysis (linear system), and response calculations (linear or nonlinear system) will need to be done. The main difference with the analysis of the internals is the method by which they are excited. There are two approaches to exciting the internals:

(1) indirect loading in which the loading is applied to the containment; and,

(2) direct loading in which the loading is applied to the internals.

In developing a test plan which includes internal testing, it will be necessary to determine if exciting the containment will cause sufficient response of the internals. In some cases it may be necessary to directly load the internals and it will be necessary to predict the levels of response.

10.3 Test Plan

The test plan would contain detailed information of the proposed tests on a test-by-test basis and a specific schedule of events. A detailed test plan, based on calculations performed in the pre-test analysis, would contain the following information:

- Stated objective of the test.
- Specification of the test specimen.
- Force type and location of force application.* For example, for tests requiring structural vibrators, the shaker location and type would be specified. For explosive testing, the location and depth of the charge would be specified.
- Relative magnitude and direction of applied force referenced to some global coordinate system.
- Required excitation levels for the particular test. For structural vibrators using rotating eccentric mass shakers, the following information would be specified:

  -- vibrator type
  -- vibrator eccentricity
  -- maximum input force at upper frequency
  -- frequency range

  For explosive tests, the following information would be required:

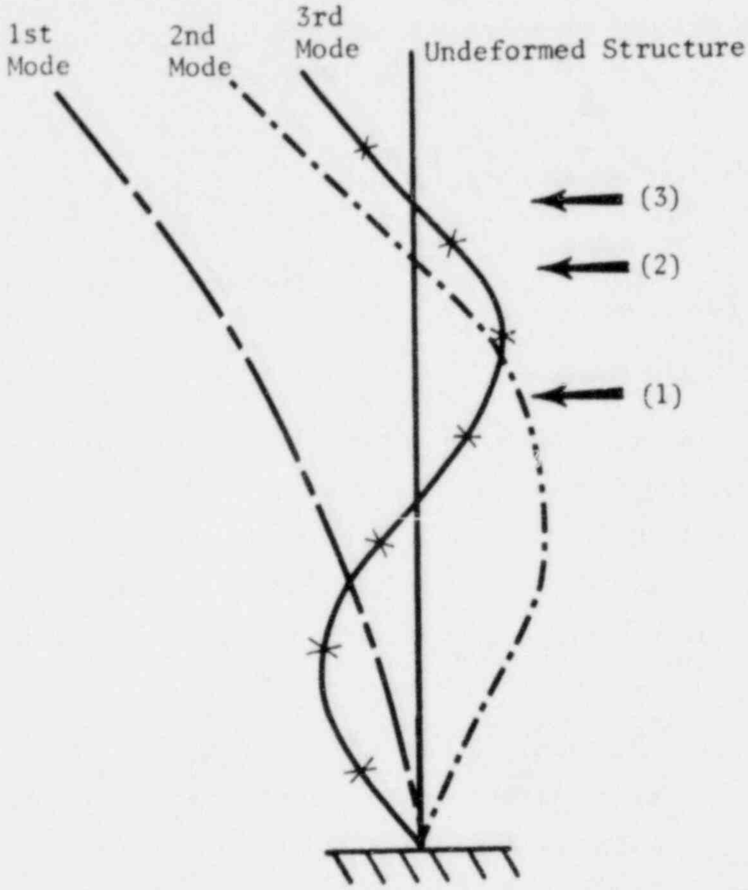
  -- charge size
  -- peak free-field acceleration anticipated or allowed
  -- frequency range
  -- distance of specimen from shot hole
- Schematic drawings specifying the type and location of transducers and also details for mounting and orientation of the instruments.
- The exact nature of the test environment would be specified. For example, if a piping system is being tested the pressure and temperature would be specified, and its water content, and support system verified.
- The required test results must be clearly stated including:

  -- identified resonant frequencies
  -- estimated damping values

---

*Care must be used in placing structural vibrators so that the applied loading will excite modes of interest (see Figure 10.1).

FIGURE 10.1: PLACEMENT OF STRUCTURAL VIBRATORS



(1) Placing a vibrator here will excite the three modes shown. It will do this equally for the three modes.

(2) Placing a vibrator here will excite the first and third modes, but not the second. The third mode may not be highly excited.

(3) Placing a vibrator here will excite the first and second modes, but not the third. The second mode may not be highly excited.

- -- identified mode shapes
- -- frequency response data
- -- achieved response levels
- -- time history data

- The format for the presentation and organization of acquired data would need to be specified including:

  - -- tabulation of natural frequencies
  - -- tabulation of modal damping values
  - -- digital computer tape of response
  - -- plots of response
  - -- Fourier transform of transient response
  - -- mode shape plots
  - -- movies
  - -- photos

The test plan specification could be computerized and stored in the digital computer used to acquire data during testing. The computer would output the test specification previously defined prior to conducting each test. The exact details for conducting the test would be given in the computer listing. An example of such a specification is illustrated in Figure 10.2.

A period of time would be required for equipment preparation and shipment. Shipping and travel arrangements to the facility would be made. Arrangements would also be made for rigidly attaching the structural vibrators to the superstructure of the RCB, scheduling for manual labor, and electrical power supply requirements on the platform.

Time would be required for setup and checkout of the structural vibrators, control systems, instrumentation and data acquisition systems at the test site. In accordance with the specifications of the test plan, an ambient survey of the dynamics of the structure will be conducted. The data acquired via the ambient survey are desired for comparison with the data acquired via the forced vibration tests.

In conducting the forced vibration tests the first step would be a series of exploratory low-level tests using the structural vibrators.

FIGURE 10.2

```
                          ANCO ENGINEERS
                        TEST SPECIFICATION

EXPERIMENT #V63.1
TEST #1       RUN #1            DATE: 10/1/79           TIME: 10.00:00
REVISION #2

PERSON RESPONSIBLE FOR TEST:
     WILLIAM E. GUNDY

PURPOSE OF TEST:
     TRANS/ROCK MODES, XX DIRECTION

SPECIMENS TO BE INSTRUMENTED:
         CONTAINMENT (RGE)
     RECIRCULATING PIPING LOOP (URL)
     REACTOR PRESSURE VESSEL (RDB)

LOCATION OF APPLIED FORCE:
     HDR CONTAINMENT (RGE)

FORCE DIRECTION AND RELATIVE MAGNITUDE:
     XX, INTERMEDIATE LEVEL

DETAILS FOR SHAKER TEST:
     MK 15
     VIBRATOR ECCENTRICITY = 6.3          KG-M
     APPLIED FORCE AT MAXIMUM OPERATING FREQUENCY = 100          KN
     LOWER BOUND OF FREQUENCY RANGE = 2.5          HZ
     UPPER BOUND OF FREQUENCY RANGE = 20           HZ

TYPES OF TEST RESULTS REQUIRED:
     IDENTIFY RESONANT FREQUENCIES
     IDENTIFY DAMPING VALUES
     IDENTIFY MODE SHAPES
     AMPLITUDE AND PHASE DATA

DATA ACQUISITION AND RECORDING TRANSDUCER LOCATIONS:
         CONTAINMENT (RGE)
         CH. #    1   RGE 16:   X
         CH. #    2   RGE 16:   Z
         CH. #    3   RGE 15:   X
         CH #     4   RGE 15:   Z
         CH. #    5   RGE 27:   Z
         CH. #    6   RGE 28:   Z
         CH. #    7   RGE 33:   X
         CH. #    8   RGE 33:   Y
         CH. #    9   RGE 33:   Z
         CH. #   10   RGE 34:   X
         CH. #   11   RGE 35:   Y
         CH. #   12   RGE 55:   X
         CH. #   13   RGE 55:   Z
         CH. #   14   RGE 77:   Y
         CH. #   15   RGE 77:   Z
         CH. #   16   RGE 100:  Y
         CH. #   17   RGE 100:  Z
         CH. #   18   RGE 197:  Y
         CH. #   19   RGE 197:  Z
         CH #    20   RGE 201:  X
         CH #    21   RGE 201:  Y
```

```
          CH. #   28   RGE 187:  Z
          CH. #   29   RGE 175:  X
          CH. #   30   RGE 175:  Z
          CH. #   31   RGE 167:  X
          CH. #   32   RGE 167:  Z
          CH. #   33   RGE 146:  X
          CH. #   34   RGE 146:  Z
          CH. #   35   RGE 128:  X
          CH. #   36   RGE 128:  Z
```

FIGURE 10.2 (continued)

```
DATA ACQUISITION AND RECORDING TRANSDUCER LOCATIONS:
     RECIRCULATING PIPING LOOP (URL)
          CH. #   37   URL 4:    X
          CH. #   38   URL 4:    Y
          CH. #   39   URL 4:    Z
          CH. #   40   URL 65:   X
          CH. #   41   URL 65:   Z
          CH. #   42   URL 100:  X
          CH. #   43   URL 100:  Z
          CH. #   44   URL 34:   X
          CH. #   45   URL 34:   Y
          CH. #   46   URL 34:   Z
          CH. #   47   URL 67:   X
          CH. #   48   URL 67:   Y
          CH. #   49   URL 67:   Z
          CH. #   50   URL 70:   X
          CH. #   51   URL 70:   Y
          CH. #   52   URL 70:   Z
          CH. #   53   URL 75:   X
          CH. #   54   URL 75:   Y
          CH. #   55   URL 75:   Z
          CH. #   56   URL 93:   X
          CH. #   57   URL 93:   Y
          CH. #   58   URL 93:   Z
          CH. #   59   URL 33:   X
          CH. #   60   URL 33:   Y
          CH. #   61   URL 82:   Z
          CH. #   62   URL 82:   X
          CH. #   63   URL 82:   Y
          CH. #   64   URL 33:   Z

DATA ACQUISITION AND RECORDING TRANSDUCER LOCATIONS:
     REACTOR PRESSURE VESSEL (RDB)
          CH. #   37   URL 4:    X
          CH. #   38   URL 4:    Y
          CH. #   39   URL 4:    Z
          CH. #   40   URL 65:   X
          CH. #   41   URL 65:   Z
          CH. #   42   URL 100:  X
          CH. #   43   URL 100:  Z
          CH. #   44   URL 34:   X
          CH. #   45   URL 34:   Y
          CH. #   46   URL 34:   Z
          CH. #   47   URL 67:   X
          CH. #   48   URL 67:   Y
          CH. #   49   URL 67:   Z
          CH. #   50   URL 70:   X
          CH. #   51   URL 70:   Y
          CH. #   52   URL 70:   Z
          CH. #   53   URL 75:   X
          CH. #   54   URL 75:   Y
```

CH. # 60 URL 33: Y
CH. # 61 URL 82: Z
CH. # 62 URL 82: X
CH. # 63 URL 82: Y
CH. # 64 URL 33: Z

FIGURE 10.2 (continued)

TYPE OF TEST ENVIRONMENT:
AMBIENT WITH WATER

REQUIRED DATA PRESENTATION AND ORGANIZATION:
TABULATION OF RESONANT FREQUENCIES
TABULATION OF CRITICAL DAMPING VALUES
DIGITAL COMPUTER MAGNETIC TAPE OF SINUSOIDAL RESPONSE
RESPONSE PLOTS OF SINUSOIDAL DATA
MODE SHAPE PLOTS

APPROVAL TO CONDUCT TEST:
ANCO PROJECT ENGINEER SIGNATURE: --------------------------------

CLIENT SIGNATURE: --------------------------------

APPROVAL OF TEST COMPLETION:
ANCO PROJECT ENGINEER SIGNATURE: --------------------------------

CLIENT SIGNATURE: --------------------------------

In the case of sinusoidal vibration, these "sweeps" would be done at various force levels over particular frequency ranges in several different directions. The exact force levels, frequency ranges and directions would be predetermined in the test-planning phase of the project. From the data acquired, an improved understanding of the fundamental dynamic characteristics of the structure would be gained.

A series of detailed sinusoidal sweeps would be done following the exploratory sinusoidal sweeps. This test series would focus on acquiring detailed data on the identified resonance frequencies. In particular, data would be taken with sufficient resolution in frequency steps necessary to accurately identify the natural frequency and to calculate critical damping coefficients for particular modes. In particular, this requires a frequency step size less than one-fourth of the smallest resonant peak bandwidth. Phase information for various channels would be monitored to quantify modal deformations.

A series of tests also would be conducted for the mode shapes of interest. This would be accomplished by holding the structural vibrators at the natural frequencies and moving a triaxial array(s) of transducers over the structure. The response levels and phases at various locations on the structure are compared to a stationary array of reference transducers. From this "response shape" data, which will be dominantly controlled by the particular mode of interest, the mode shapes can be determined.

For explosive testing, much of the previous discussion on forced vibration testing, i.e., shipping, scheduling for labor, setup and checkout of instrumentation and data acquisition systems, and conducting of tests, applies. For each explosive test, it will be necessary to place the required explosive charge(s). Additional accelerometers (in addition to containment instruments) will be placed in the ground surrounding the containment.

If the containment internals are to be tested, it will be necessary to utilize the subject equipment. It may be desirable to include in the test plan an ambient survey of the internals. These data are useful in determining how much of the response is due to harmonic forcing or explosive loading and how much is due to ambient excitation.

10.4 Post-Test Analysis

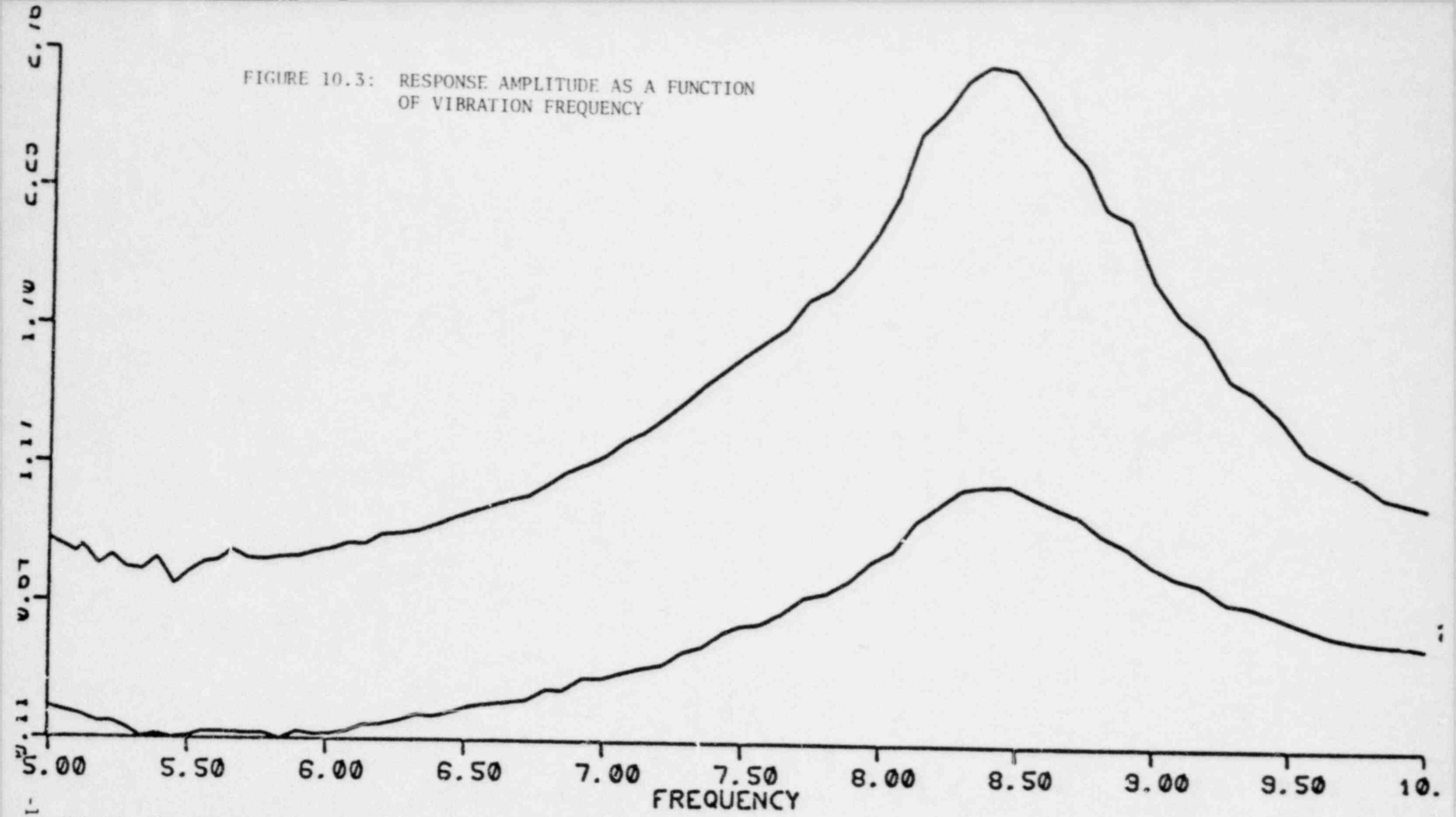
The analytical model and test data would be compared and interpreted to: (1) verify the validity of the analytical model; and (2) update the parameters used to define the analytical model to obtain improved correlation between the analysis results and the test results. This task involves:

(1) detailed analysis of the test data;
(2) assessment of reliability of test data;
(3) assessment of uncertainties in model parameters; and,
(4) tuning of model parameters using parameter identification.

The detailed data analyses include: (1) the generation of steady-state response amplitude versus vibrator excitation frequency plots (as illustrated in Figure 10.3) for various accelerometer locations for forced vibration tests; (2) time history plots of accelerometer data (explosive, initial displacement transient response, or other transient loading tests); or (3) Fourier transforms of various time histories. These analyses yield resonance frequencies and damping values for various vibrator positions/force levels, for various explosive charge locations and sizes and for various snapback forces. The mode shapes as illustrated in Figure 10.3 would be determined from the transfer function of the acceleration responses (amplitude and phase) at various locations and with given applied forcing.

The reduced test data will be compared with the analytical model of the structure to refine the structural stiffness, mass, and damping parameters. For this purpose the Bayesian identification technique discussed in Section 7.5 would be used.

FIGURE 10.3: RESPONSE AMPLITUDE AS A FUNCTION OF VIBRATION FREQUENCY



SAME AS EARLIER BUT 5 - 10 HERTZ, 5.81 KG-M NS
TRANSDUCER 7 NS SE CORNER
TRANSDUCER 8 VERT SE CORNER

1 TEST 2 RUN 1 TRANSDUCER 7 MODULUS 2 TEST 2 RUN 1 TRANSDUCER 8 MODUI

10.5 Scheduling and Budget

The time and costs required to perform a test depend on the objectives and scope of the test. The scope may vary from a simple ambient survey with one or two instruments and a portable spectrum analyzer to a large test program using both sinusoidal vibrators and transient excitation, 100 transducers, and an on-site computerized vibration analysis system. The ambient survey could yield a rough confirmation of the first few resonant frequencies and would cost a few thousand dollars. The large test program would answer questions regarding the dynamics of the plant and its internals and the validity of their modeling and would cost over a million dollars. The simple test may require a few days for preparation, execution and reporting. The comprehensive tests may involve more than one year of pre- and post-test work, and many weeks of testing. Many possibilities exist between these two extremes.

For budgeting and scheduling it is assumed that the containment structure of a typical PWR nuclear power plant is to be tested using both sinusoidal vibrators and blast excitation. The desired data are resonant frequencies, damping ratios, and mode shapes of the containment structure in the frequency range of 0-10 Hz. Nonlinear trends between 10^{-3} to 10^{-1} g acceleration response are also to be documented. This test program approaches the upper limit of the above-mentioned extremes.

Two selected internal components are also to be studied. These are chosen to be a loop of the primary coolant system and the polar crane. (We have found that scheduling and costs are relatively insensitive to soil conditions and the type of reactor tested; that is, whether the plant is a PWR or a BWR.) Pre-test planning includes finite element models (of moderate complexity) of the containment and the two components. Testing of the components includes excitation by containment motion, but emphasizes snapback and sinusoidal forces applied directly to the components. Approximately 50 acceleration transducers and 50 strain gauges are monitored with an on-site computerized vibration analysis system. The post-test analysis includes full digital data documentation, graphical data presentation, and parameter identification to estimate theoretical model validity.

The time and cost involved in doing the pre-test analyses, testing and post-test analyses for the typical PWR containment structure and two internal structures are outlined in Tables 10.1 through 10.3. The total manpower effort plus additional direct costs needed to perform these tasks is approximately 7,000 hours plus $200,000. The tasks described in this example make the test very detailed, involving a fair amount of preparation, testing and data reduction. These numbers are estimates only and could easily vary by ±50 percent depending on the specific requirements of the project.

TABLE 10.1: PRE-TEST ANALYSIS OF EXAMPLE PWR SYSTEM (Approximately five elapsed months would be required to perform this analysis)

1. Finite element model of containment building (includes eigenvalue analysis).
2. Excite containment model for harmonic and explosive loading; determine response (i.e., acceleration, stress, etc.)
3. Finite element model of a loop of primary coolant loop (includes eigenvalue analysis).
4. Excite coolant loop model for containment motion, and harmonic and snapback loading; determine response.
5. Finite element model of polar crane (includes eigenvalue analysis).
6. Excite polar crane model for containment motion, and harmonic and snapback loading; determine response.
7. Costs for pre-test: Manhours = 1,500*
   Direct Costs = $20,000**

---

*Specified separately from direct costs.

**Mainly computer costs.

TABLE 10.2: TESTING OF EXAMPLE PWR SYSTEM (Approximately two months of testing are involved)

1. Equipment checkout and shipping.
2. Personnel air travel.
3. Setup of test system (place accelerometers, route electrical cables, setup of computer system, placement of strain gauges, etc.)
4. Preliminary tests to verify integrity of test system.
5. Detailed forced vibration tests (FVT) of containment building.
6. Detailed explosive tests of containment.
7. Detailed FVT of a loop of primary coolant system.
8. Detailed snapback tests (SBT) of primary coolant system.
9. Detailed FVT of polar crane.
10. Detailed SBT of polar crane.
11. Equipment rental.
12. Personnel per diem.
13. Costs for testing: Manhours = 4,000
    Direct Costs = $160,000*

---

*Mainly equipment rental, but also shipping, travel and per diem.

TABLE 10.3: POST-TEST ANALYSIS OF EXAMPLE PWR SYSTEM (About three months are required for this task)

1. Digital data documentation.
2. Selection of data to be plotted.
3. Plotting of data.
4. Parameter identification (simplistic).
5. Writing of report.
6. Costs of post-analysis:

   Manhours = 1500
   Direct Costs = \$20,000*

---

*Mainly computer costs.

APPENDIX A

TYPICAL PWR SEISMIC DESIGN INFORMATION

Table of Contents

SEISMIC CLASSIFICATION OF STRUCTURES, SYSTEMS, COMPONENTS AND THEIR CAPABILITY

Design Class	Design Class I	Design Class II	Design Class III
APPLICABILITY	Plant features important to safety, including plant features required to assure (1) the integrity of the reactor coolant pressure boundary. (2) The capability to shut down the reactor and maintain it in a safe shutdown condition. (3) The capability to prevent or mitigate the consequence of accidents which could result in potential off-site exposures comparable to the buideline exposures of 10 CFR 100.	Plant features important to reactor operation, but not essential to reactor safety.	Plant features not related to reactor or safety
SEISMIC DESIGN REQUIREMENTS	Plant features required to meet AEC GDC-2 and proposed Appendix A to 10 CFR 100. Plant features designed to withstand effects of Double Design Earthquake (DDE)	Plant features *not required* to meet AEC GDC-2 and proposed Appendix A to 10 CFR 100. Plant features *not* designed to stand effects of DDE.	
SEISMIC CAPABILITY	Containment building B designed to acceleration level 0.65 G. Refer to Tables 1,2, and Figure 1,2.	Seismic design level of non-safety related systems is not included in the reactor safety report . The acceleration level of current reactor project is 0.2 G.	

SEISMIC CLASSIFICATION OF CONTAINMENT STRUCTURE AND INTERNAL EQUIPMENTS

CONTAINMENT STRUCTURE AND INTERNAL SYSTEMS	CONTAINMENT INTERNAL COMPONENTS	DESIGN CLASS
1. Containment Structure	containment structure	I
	containment liner	I
	containment penetrations and air locks	I
	containment piping rupture restraints	I
	containment interior concrete	I
	containment penetration flued heads	I
	reactor cavity liner	II
2. Facilities	containment structure polar crane	I
	missile shield over Control Rod Drive Mechanism (CRDM)	I
	reactor vessel internal support stands	II
3. Reactor coolant system and equipment supports	reactor vessel support structure	I
	steam generator supports	I
	steam generator hydraulic support struts	I
	reactor coolant pump supports	I
	reactor coolant piping restraints	I
	pressurizer support	I
	reactor vessel	I
	vessel head lifting device	I
	reactor vessel upper internals	I
	reactor vessel lower internals	I
	steam generator, primary and secondary tube	I
	reactor coolant pump	I
	pressurizer	I
	RTD bypass manifold	I
	vessel insulation	II
	pressurizer heaters	II
	pressurizer relief tank	II
	all system piping to the pressurizer relief tank	II
	all drain lines of the system	II

CONTAINMENT STRUCTURE AND INTERNAL SYSTEMS	CONTAINMENT INTERNAL COMPONENT	DESIGN CLASS
Reactor coolant system and equipment supports (continued)	reactor vessel	I
	vessel head lifting device	I
	reactor vessel upper internals	I
	reactor vessel lower internals	I
	steam generator, primary and secondary tube	I
	reactor coolant pump	I
	pressurizer	I
	RID bypass manifold	I
	vessel insulation	II
	pressurizer heaters	II
	pressurizer relief tank	II
	all system piping to the pressurizer relief tank	II
	all drain lines of the system	II
4. Containment HVAC	containment fan cooling system	I
	containment purge valves and plenums	I
	plant exhaust vent	I
	forced draft shutter damper	I
	containment fan cooling system annular ring	II
	CRDM ventilation system	II
	Incore instrument room air conditioning system	II
	Iodine removal system	II
	containment refueling water surface system	II
5. Reactor incore flux mapping associated items	instrument conduit and couplings	I
	seal table and parts	I
	flux thimble tubing	I
6. Control Rod Drive mechanisms (CRDM)	full length CRDM pressure housings	I
	part length CRDM pressure housings	I
	CRDM seismic superintendent	I
7. Fuel and rod control cluster assemblies	fuel assemblies	I
	full length rod internal cluster assemblies	I
	part length rod control cluster assemblies	I
8. Fuel transfer system	fuel transfer tube and flange	I
	reactor internal lifting rig	I
	reactor vessel head lifting rig	I
	fuel inspection fixture	II
	refueling machine	II
	reactor cavity manipulator crane	III

CONTAINMENT STRUCTURE AND INTERNAL SYSTEMS	CONTAINMENT INTERNAL COMPONENT	DESIG CLASS
9. Channel volume control system (CVCS)	excess letdown heat exchanger-tube side	I
	regenerative heat exchanger-tube side	I
	excess letdown heat exchanger-shell side	II
	regenerative heat exchanger-shell side	II
	all drain lines and vent lines of the system	II
10. Safety injection system (SIS)	safety injection accumulator tanks	I
	SIS test lines	II
	SIS vent lines	II
	SIS accumulator interconnection lines	II
11. Residual heat removal system	containment emergency sump	I
12. Nuclear steam supply system (NSSS) sampling system	all pipes and valves inside the containment	I
13. Containment spray system	six rings of spray nozzles	I
14. Nuclear service cooling water system	containment cavity cooling coil	I
	containment cooler	I
	containment building auxiliary air cooling coil	I
15. Liquid radwaste system	reactor coolant draink tank	II
	reactor coolant drain tank pump	II
	reactor coolant drain tank heat exchanger	II
	all pipes and valves connect to the RCDT	II
	containment structure sump pump	II
	reactor cavity sump pump	II
16. Post accident hydrogen removal system	electric hydrogen recombiner	I
17. Compressed air system	all pipes and valves inside the containment	I

CONTAINMENT STRUCTURE AND INTERNAL SYSTEMS	CONTAINMENT INTERNAL COMPONENT	DESIGN CLASS
18. Fire protection system	all pipes and valves inside the containment	II
19. Main feedwater system	pipes from steam generator to the main feedwater isolation valves	I
20. Main steam system	pipes from steam generator to the main steam isolation valves	I

APPENDIX B

NOTES ON PIPING STRESS CALCULATIONS AND MONITORING

Class 1 Piping Systems

Two limits on structural response during Level A Service Limits (Normal Operating Conditions) are imposed on Class 1 pipes by the Code. The first limit, given by Eq. (10) of Subsection NB-3653 (denoted NB-10 herein), assures shakedown and elastic action after the first few load cycles. The second limit, given by Eq. (11) of Subsection NB-3653 (denoted NB-11 herein), assures that fatigue failure does not occur.

Shakedown occurs if the primary plus secondary stress intensity S_n is less than or equal to 3.0 S_m where S_m is an allowable stress intensity; that is,

$$S_n = C_1 \frac{P_o D_o}{2t} + C_2 \frac{D_o}{2I} M_i + \frac{1}{2(1-\upsilon)} E\alpha|\Delta T_1| + C_3 E_{ab}|\alpha_a T_a - \alpha_b T_b| \leq 3.0\ S_m \qquad \text{(NB-10)}$$

In Eq. (NB-10), the first term on the left side of the inequality is the range of primary membrane stress intensity due to the range of operating pressure P_o, the second term is the range of primary bending stress intensity due to the range of resultant moment M_i and the last two terms are secondary stress intensities due to the range of thermal loads. C_1, C_2, and C_3 are secondary stress intensity factors, D_o is the outside diameter of the pipe, t is the wall thickness and I is the moment of inertia. Other terms are defined in Subsection NB-3653.

The range of allowable resultant moment during testing is obtained by solving Eq. (NB-10) for M_i; this gives:

$$M_i \leq \frac{1}{C_2} \frac{2I}{D_o} \left\{ 3.0\ S_m - C_1 \frac{P_o D_o}{2t} - \frac{1}{2(1-\upsilon)} E\alpha|\Delta T_1| - C_3 E_{ab}|\alpha_a T_a - \alpha_b T_b| \right\} \qquad \text{(a)}$$

where the resultant moment is:

$$M_i = \sqrt{M_x^2 + M_y^2 + M_z^2} \qquad \text{(b)}$$

and M_x and M_y are the bending moments in the plane of the pipe cross section and M_z is the torsional moment.

The allowable value of M_i is dependent on the plant operating conditions at the time of testing because the range of pressure and thermal loads is dependent on plant operating conditions.

Fatigue failure does not occur if the peak stress intensity range S_p does not cause accumulated damage exceeding Miner's rule. S_p is given by Eq. (NB-11); that is,

$$S_p = K_1 C_1 \frac{P_o D_o}{2t} + K_2 C_2 \frac{D_o}{2I} M_i + \frac{1}{2(1-\upsilon)} K_3 E\alpha |\Delta T_1| + K_3 C_3 E_{ab} |\alpha_a T_a - {}_b T_b|$$

$$+ \frac{1}{1-\upsilon} E\alpha |\Delta T_1| \qquad \text{(NB-11)}$$

where K_1, K_2 and K_3 are local stress indices.

The alternating stress intensity S_{alt} is one-half of S_p and is used to determine the allowable number of load cycles. Eq. (NB-11) can be solved for an allowable value of M_i such that the additional test load cycles do not violate the fatigue limit.

Class 2 Piping Systems

Limits are imposed on the structural response of Class 2 pipes subject to sustained loads and occasional loads. Occasional loads include earthquake loads.

By Eq. (9) of Subsection NC (denoted NC-9 herein), the occasional stress intensity S_{OL} should be less than 1.2 S_h where S_h is the basic material allowable stress at the design temperature; that is,

$$S_{OL} = \frac{PD_o}{4t_n} + 0.75\ i\ \left(\frac{M_A + M_B}{Z}\right) \leq 1.2\ S_h \qquad \text{(NC-9)}$$

where M_A is the resultant moment due to weight and other sustained loads, M_B is the resultant moment due to occasional loads including (but not limited to) earthquake loads, Z is the section modulus and i is the stress intensification factor ($0.75\ i \geq 1.0$).

The allowable resultant moment during testing is obtained by solving Eq. (NC-9) for M_B; this gives:

$$M_B \leq \frac{Z}{0.75\ i} \left(1.2\ S_h - \frac{PD_o}{4t_n}\right) - M_A \qquad \text{(c}$$

Monitoring

Monitoring of the structural response of piping systems to satisfy the safety criterion can be accomplished by strain gauging to determine stresses and resultant moments at the hot spots. The resultant moments can be compared to the allowable moments given by Eq. (a) or Eq. (c) and the testing terminated when the allowable values, or a fraction of the allowable values, are exceeded. Alternatively, the stresses can be monitored and the testing terminated when the Tresca yield criterion or the von Mises yield criterion (or fractions thereof) is exceeded.

The locations of hot spots are obtained from the stress analysis. If the hot spots cannot be monitored because of surrounding equipment or high radiation levels, then the strains from other locations can be linearly scaled.

The following method has been used by ANCO personnel to monitor strains and resultant moments during snapback testing of Class 2 pipes at Indian Point 2. At selected locations on the pipe, a strain rosette was mounted as well as an additional linear gauge along the longitudinal axis of the pipe. The output from this gauge pattern was the longitudinal strain at two locations εx_1 and εx_2 and the shear strain γ_{xy}. This output is the minimum output necessary to calculate the resultant moment which is:

$$M_i = \frac{EI}{D_o/2}\sqrt{\varepsilon x_1^2 + \varepsilon x_2^2 + \left(\frac{\gamma_{xy}}{1+\upsilon}\right)^2} \qquad \text{(d)}$$

where E is the elastic modulus of the pipe material and υ is Poisson's ratio.

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15. SUPPLEMENTARY NOTES

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16. ABSTRACT *(200 words or less)*

This study reviews experimental techniques, instrumentation requirements, safety considerations, and benefits of performing vibration tests on nuclear power plant containments and internal components. The emphasis is on testing to improve seismic structural models. Techniques for identification of resonant frequencies, damping, and mode shapes, are discussed. The benefits of testing with regard to increased and more accurate computer models are outlined. A test plan, schedule and budget are presented for a typical PWR nuclear power plant.

17. KEY WORDS AND DOCUMENT ANALYSIS

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17b. IDENTIFIERS/OPEN-ENDED TERMS

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