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This study reviews past projects, experimental techniques, instrumentation requirements, safety considerations, and the benefits of performing vibration tests on nuclear power plant containments and internal components. The emphasis is on testing to improve seismic structural models although the methods are applicable to any form of dynamic excitation. Established techniques for testing and for identification of resonant frequencies, damping, and mode shapes are presented. The benefits of testing with regard to verifying increased damping values and establishing more accurate computer models are outlined. Finally, a forced vibration test project planned to realize these benefits is presented for a typical nuclear power plant.

1. Summary

Unlike many conventional structures which are subject to less rigorous constraints, nuclear power plants must evoke a high degree of confidence in meeting their very strict design requirements [2]. The goal of this paper is to present and discuss factors relevant to a decision on whether or not to use test data to verify and improve on the dynamic analysis and theoretical modeling of nuclear power plant containment buildings and internal equipment. In situ vibration tests of nuclear power plants, conducted at over 30 sites, have provided valuable information on design adequacy, have measured higher damping values than those stipulated by regulatory standards, and have usually demonstrated an increased seismic capacity of the test facility. The techniques and justifications for such testing have been extensively developed over the last ten years. Table 1 lists selected nuclear power plants subjected to dynamic testing in recent years.

For example, vibration tests at the San Onofre Nuclear Generating Station (SONGS) were first conducted in 1969. 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 (~18% of critical) in the lower modes of vibration, even at low (10^{-3} g) acceleration response. Studies of the coolant loops led to improved mathematical models and structural modifications to achieve greater seismic capacity. More recently (1978) vibration tests were performed at the Diablo Canyon Nuclear Power Plant 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 (0.4–0.75 g). Earlier vibration tests on other containments (such as SONGS) had demonstrated high values of damping and were used to justify higher values 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}–10^{-1} g) and piping systems (10^{-1}–10^{1} g). Damping of 5% was found at moderate levels of containment response; high level tests produced damping estimates up to 8% at 10^{-1} g response. Tests on 1/8–1/48th scale containment models, sponsored by the Electric Power Research Institute (EPRI), have been conducted to scaled accelerations of 0.3 g using buried explosives and

Table 1
List of selected nuclear power plants subjected to dynamic testing in recent years

Plant name (Date)	Location	Test/analysis Organization	Purpose of testing/ Test methods	Major test subjects	Significant aspects of testing/reference
Diablo Canyon (1977)	CA	ANCO Engineers Santa Monica, CA	Model verification to support licensing activities/snap-back, sinusoidal at response levels in range of 0.1–1 g for piping systems, from 0.03–0.2 g for balance of systems	Six piping systems, fluid tanks, heat exchangers, gas storage vessels, valves	Excited by direct load application to test object; determined frequencies, modal damping, mode shapes; used results for some design modifications where indicated; pipe restraint stiffness measured. Piping system damping varied from less than 1 to nearly 15%, depending upon amplitude, degree of restraint, pipe dimensions. Typical piping behavior was that more flexible systems exhibited higher damping in lower modes. Piping system example by mode: 7–8% first 3 modes, 4–5% damping for second 3 modes. The high value of 15% was measured at low levels of response; friction effects were overcome and dropped to 7% at ~1 g. Piping system no. 2: 3–4% damping for first three modes at ~1 g, next two modes at 1–2%. Valves: 1–4%, with 2% typical. Diesel generator – first two transverse/rocking modes were 5% damped at 0.2 g; higher modes 2–3%. [ANCO Report 1122-4.b. Vols. 1–9 (Proprietary).]
Indian Point – 1 (1979, 1980)	New York [a]	ANCO Engineers Santa Monica, CA	Nonlinear piping-dynamics research and effects of modern support hardware at moderate response/ levels/sinusoidal and snap-back testing	Feedwater piping: 20 cm diameter, 30 m length	Testing system as-built and after installation of variety of supports in different configurations. Peak amplitudes >2 g; peak uniaxial strains 20% of yield in first phase of testing. Damping ~2% for lightly supported original design. Modified systems to be tested late 1980 at higher strain levels
Indian Point – 2 (1972)	New York	Westinghouse	Linear regime piping dynamics research/ sinusoidal	Primary coolant loop	Peak amplitudes: 0.1–1% g. Damping from 1–5% of critical [Westinghouse report WCAP-7920 (1972).]

Heissdampfreaktor [b] (1975, 1979)	Fed. Rep. Germany	ANCO Engineers Santa Monica, CA	Research in small amplitude and moderate amplitude nuclear power plant dynamics/snap-back, sinusoidal, impact, blast testing, rocket tests	Containment building, primary coolant piping, experimental piping, reactor pressure vessel, flood water storage tank	1975 tests – excited up to ~1% g on containment, 0.5–40% g on equipment maximum piping strain less than 5% of yield strain. 1979 tests – Using 110 ton (1100 k N) shaker forces, containment excited to ~6% g at fundamental, equipment up to 1 g; one piping system loaded above yield on one or more strain gauges. Containment damping: 1–6% (fundamental about 1.5 Hz, force $\simeq$ 36 tons) 3–4% in higher modes [ANCO Propriety Reports; also SMiRT-4, paper K8/5; and SMiRT-5, papers K13/2, K13/3.]
Kernkraftwerk Phillippsberg – 1 (1976)	Fed. Rep. Germany	ANCO Engineers Santa Monica, CA	Model verification study for licensing support/snap-back; peak responses ~0.2 g, ~1.0 cm	Piping for ECCS; approximately 20 m length by 0.25 m diameter; piping system strongly restrained	First mode theoretical frequency was 35% less than that measured and was 25% less after model modifications which reflected 'as-built' conditions. Analysis performed by separate companies with comparable results. Piping system appeared stiffer than expected; hypothesized was support effect. Nonlinear effects significant at low response levels. At high response (with gaps shimmed), first mode was 9% damped at 2.1 Hz. Next seven modes $\beta > 6\%$ (up to 5 Hz); next eight, $\beta \simeq 2$–4%, average about 3%. Reanalysis with experimentally based models indicated seismic loads were overestimated in design by factor of two. [ANCO Proprietary Report 1098-2.]
Fukashima – 1 (1969) See Shimane test below for comparison investigation)	Japan	Muto Institute et al., Tokyo	Research to investigate site effects for two identical plants on different soils (see Shimane test below). Plants were 460 MWe BWR/ sinusoidal	Containment building	Excited in refueling floor with peak sinusoidal forces up to three tons; peak amplitudes of order 10^{-4} g's on refueling flood Fukashima in firm soils; shear wave velocity, 2000 ft/s; pressure wave velocity, 5576 ft/s. (This site had shear wave velocity of only 1/3 of Shimane site.) Results: Mode – Period – (Frequency) – Apparent damping 1 – 0.25 s – (4.9 Hz) – 34% 2 – 0.17 – (5.9 Hz) – 8% 3 – 0.089 – (11.2 Hz) – 5% [SMiRT-2, paper K5/3.]

Table 1 (continued)

Plant name (Date)	Location	Test/analysis Organization	Purpose of testing/ Test methods	Major test subjects	Significant aspects of testing/reference
Shimane (1972)	Japan	Muto Institute et al., Tokyo	Research to investigate site effects for two identical plants on different soils (see Fukashima text above). Plants were 460 MWe BWR/ sinusoidal	Containment building	Same test conditions as above except site was rock; shear wave velocity, 5900 ft/s; p-wave velocity, 12 140 ft/s; Youngs modulus, 220 ton/cm^2, about 12 times greater than Fukashima site. Results: Mode Period (Frequency Apparent damping 1 0.19 (5.3 Hz) 2% 2 0.13 (7.7 Hz) 5% 3 0.086 (11.6 Hz) 5%
Fugen (1979)	Japan	Takasago/ Mitsubishi Tokyo	Verification of dynamic parameters used in seismic design for licensing purposes/sinusoidal and snap-back	Primary coolant piping and feed-water piping in BWR pressure-tube reactor (165 Mwe D_2O moderated)	Tested 267 mm to 508 mm outside diameter piping runs. Forces limited to 220 lbs (980 N) on primary piping and 110 lbs (490 N) on feedwater piping. Peak response levels about 0.1 *g* on feed-water piping; about 0.02 *g* on primary piping. In all tests gaps closed to eliminate nonlinear effects from seismic support elements. Results showed primary piping damping at 6% at 13.5 Hz first mode, 8% second, 2% third, 6% fourth, 6% fifth, 3% sixth; 1% seventh, unspecified eighth, and 7.5% ninth (at 19.6 Hz). The primary system was complicated, consisting of down comers, headers, manifolds. Feedwater piping relatively simple, smaller diameter (267 mm) with 5 straight runs and 6 elbows, 12 snubbers, plus spring and constant force hangers. Test results were damping of 0.7% first mode (8.6 Hz), 2.1% second mode, 4.5% third mode (17.0 Hz). Agreement between analysis and results good only in lower modes. [SMiRT-5, paper K13/8.]

Hamaoka 1 and 2 (1973, 1974, 1977)	Japan	Chubu Electric/ Takenaka Technical Research Lab., Tokyo	Research in soil–structure interaction and through space soil coupling of two BWR/sinusoidal *Additional Note*: SMiRT-4, paper K2/16, reports that 1 ton force produced peak response of about 7.5 microns at 4.6–4.8 Hz first and second mode and damping of 23% each mode. Paper K13/4 suggests that force increase of 18 times reduces first and second mode frequency to 2.5 Hz and 3.4 Hz and increases β to 40–50%.	Containment building tested with forces up to 100 tons; forces applied to refueling floor of BWR MK1-type plant	1973, 1974 – low level tests of unit 1; papers K3/2, K2/16 (SMiRT-3, SMiRT-4) 1977 – higher level tests (SMiRT-5, paper K13/4. At maximum force at first mode (about 18 tons at 2.5 Hz), generated peak displacement of 10 microns or 2.5 × 10^{-4} g's at 2.5 Hz. Results of testing at accelerations up to 3 × 10^{-3} g's (0.3% g) gave following containment building results for east-west direction (N–S about same.) Freq. (Hz) – Damping (% of critical) 2.49 – 39.6 3.44 – 49.3 4.63 – 19.9 5.02 – 20.4 5.67 – 19.2 6.11 – 17.2 6.59 – 15.2 7.08 – 3.1 7.50 – 2.7 7.89 – 13.5 8.70 – 12.4 9.14 – 15.6 1–4 Hz were soil–structure modes; 4–5.7 Hz were building-building interaction effects; Site soil shear were velocity, 2600 ft/s (800 m/s); unit weight, 125 lb/ft^3 (density of 2.01 ton/m^3 SMiRT-3, paper K3/2; SMiRT-4, paper K2/16; SMiRT-5, paper K13/4.

Table 1 (continued)

Plant name (Date)	Location	Test/analysis Organization	Purpose of testing/ Test methods	Major test subjects	Significant aspects of testing/reference
Humboldt Bay (1974)	CA, U.S.A.	ANCO Engineers Santa Monica, CA	Modeling verification to support seismic upgrading to new criteria/sinusoidal and snap-back testing	Storage tanks, pumps, motors, valves, electrical cabinets, piping, turbine pedestrials, containment, stack	Five case studies reveal the benefits of testing: case one is a liquid poison tank, the testing of which was used to simplify the model of the existing tank and define stiffness properties for use in the analysis. Case two involved the high level in situ proof testing of an emergency generator. Case three test results, for the Reactor Control Board, indicated the need to stiffen several panels and provided the necessary information for the development of a model which was used to predict input spectra for selected instruments mounted on the panel. Certain of these instruments were subsequently shake-table tested by others according to the developed spectra. The fourth case involves a 250 ft ventilation stack. Test data were used to verify the analysis of the stack. The final case concerns testing of the control room floor. Test results pointed out the need for structural modification. The basic conclusion of this paper is that in situ testing is a feasible and useful method to improve and guide theoretical studies and seismic design of nuclear power plant equipment and structures. [SMiRT-4, paper K8/3.]
San Onofre Unit 1 (1969–1972)	CA, U.S.A.	ANCO Engineers Santa Monica, CA and UCLA	Model verification and research investigation of dynamics. Creation of validated models/sinusoidal		Excitation of the containment with up to 5 tons of force was used to investigate soil–structure interaction and primary loop dynamics. Results were compared to San Fernando earthquake response and to analytical models. Soil–structure modes were found to be highly damped (16–18% @ 10^{-3} g sine tests, 20% at 10^{-2} g earthquake). Damping in primary loop ranged from 1.5–4.0% at 10^{-2}–10^{-1} g. Models of varying degree of sophistication were fit to the data and led to equipment support modifications. [Nucl. Engrg. Des. 25 (1973) 51–94.

Quad Cities (1972)	Illinois, U.S.A.	UCLA and ANCO Engineers	Containment dynamic research. Ambient and impact	Containment	Testing to plan longer program to validate models. Frequencies and damping were identified at very low response amplitudes. [ANCO internal memorandum.]
VAK (1975, 1979)	Kahl, Fed. Rep. Germany	ANCO Engineers, Santa Monica, CA	Monitoring to assure no regulatory implication during nearby testing of Heissdampfreaktor (HDR)/Blast testing	Containment, primary coolant loop	Response to 10 kg blasting 200 meters distant measured. Results compared to analysis and used to demonstrate safety of plant. Heissdampfreaktor (See entry of HDR)
PEC (1972–1974)	Bologna, Italy	CNEN Roma	Forced vibration tests of validate models and effects of modifications. Ambient and sinusoidal	Containment and crane bridge structure	Ambient survey and shaker methods were found useful in identifying ovaling and breathing modes with minimum plant operation disruption. Model structures were also tested. Resonant frequencies of all three sources agreed to within 10%. [SMiRT-2, paper K5/4, SMiRT-3, paper K6/8.]
ENEL IV (1976)	Caorso, Italy	ISMES Bergamo	Ambient and forced vibration to validate test methods and computer models. Also correlated with actual earthquake responses. Sinusoidal and earthquake.		Damping of 10–15% measured, along with 10 modes 3–16 Hz. Effects of water level in pool investigated. Experimental frequencies higher than computed. [SMiRT-4, paper K8/4.]
MAPP, RAPP (1975)	Two plants in India	PPED, Dept. of Atomic Energy, India, University of Roorkee	Snapback tests to determine frequency and damping to evaluate seismic capacity.	Internal equipment (condensers, tanks, heaters.)	Up to two tons of force were used to excite equipment. Damping from 1.6–6.5% measured. Found that piping attached to equipment greatly increased equipment damping. [SMiRT-4, paper K8/7.]
Tokai – II	Japan		Investigate the safety of the seismic design via parameter investigation and research for future design purposes. 150 tons maximum force at BWR refueling floor with sinusoidal force	Containment building of 1100 MWe BWR	First mode damping with soil–structure interaction effects was estimated at 15–25% versus the value of 5% used in design. [Proc. 5th Japan Earthquake Engineering Symposium, Tokyo, 1978.]

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[a] At time of test initiation no test amplitudes was permitted which would impair IP1 license. Thus, was tested consistent with any operational plant.

[b] Test amplitudes limited by licensing considerations; later blowdown testing required strict dynamic test control during 1975 tests. 1979 tests permitted larger amplitudes.

eccentric mass shakers. The results indicate very high values of damping (10–20%) and the importance of nonlinear soil–structure interaction. Other test programs support these observations and are discussed herein. Similar data have resulted from internal equipment and piping tests.

A variety of testing methods is available for exciting containment structures to any reasonably desired level of response (10^{-1}–10^{0} g). The most promising and field-proven are eccentric mass sinusoidal vibrators (with forces up to 4×10^6 N and 10^6 lb) and the use of buried explosives (expending several tons of explosives). Linear hydraulic actuators, impulsive shear rams, and rockets are also potentially useful, but have not been as thoroughly proven as the aforementioned excitation techniques. 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 equipment alone is to be tested, direct excitation is preferable to containment excitation. Instrumentation for such testing is 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 ultimately depends on the specific plant, soil conditions, surrounding buildings, project goals, 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 measures of 'damage'). In conflict with this requirement is the desire to test to the highest response levels acceptable to demonstrate the maximum [1] damping possible and to document nonlinear trends in the response. Test programs have led to reductions in predicted seismic response by factors of 1.2 to greater than 2.0 (15–50% less response), depending upon system design, materials, erection, and boundary conditions. These reductions have been the product of nonlinearities as well as conservative design criteria.

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 believe that containment responses on the order of 50–100% of what would be generated by the predicted Operating Basis Earthquake (OBE) motion are acceptable during testing. Plants designed for higher seismic capacity 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 are generally greater than those required to demonstrate the validity of models and provide more realistic 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 are useful to the understanding and modeling 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 mass and stiffness or soil properties) in order to match more closely 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 test scope and goals. Simple tests to determine a few resonant frequencies and dampings on simple equipment can be carried out for a few thousand US dollars. Extensive research efforts, involving both theoretical and experimental investigation, of 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 and scheduling is presented later in this paper.

2. Testing experience

2.1. Introduction

Vibration tests have been conducted at nuclear reactor facilities in the United States and interna-

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[1] Energy dissipation is typically amplitude dependent and almost always has been observed to increase with increased response.

tionally since 1965.[2] These tests have measured either (1) the response to ambient vibrations; or (2) the response to forced vibrations caused by either 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 measure specific dynamic parameters such as eigenfrequencies, mode shapes and damping ratios;

(2) to study nonlinear trends in dynamic characteristics;

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

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

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

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

2.2. Tests of nuclear power plants containment (soil–structure interaction)

An important aspect of seismic design is to determine the effects of soil–foundation interaction on structural response. This importance in the dynamic characteristics of massive structures such as nuclear power plants has been known for some time. 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 [3] in which 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 et al. [4] have reviewed seismigraph records obtained during actual earthquakes and inferred the extent and significance of the soil–structure interaction. In addition, strong interactions have been observed on heavy equipment and their foundations when subjected to strong ground motions produced by buried explosives [5].

Soil compliance effects on the earthquake response of nuclear power containment structures and internal equipment are a significant aspect of nuclear facility design. EPRI has initiated an analytical and experimental research program to investigate *nonlinear* soil–structure interaction effects on nuclear power plants [6]. 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 [44]. Realistic methods for treating the nonlinear characteristics of soils may permit the derivation of more representative site response spectra than those resulting from current regulatory procedures. It is anticipated that lower design spectra will result for a specific site input.

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 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-eighth the size of a full-scale nuclear power plant containment building [6]. The models were subjected to a simulated earthquake produced by detonating up to 70 000 kg of buried explosives within 100 m of the test object. The results indicate that nonlinear soil response is very important at higher levels of response ($>0.1\,g$).

Soil–structure interaction has been recognized internationally as an important issue. Two experimental programs carried out in Japan, for example, were a full-scale test using the JPDR Plant and model tests [43]. Forced vibration tests using horizontal excitation for each model were carried out with an eccentric mass vibrator installed on the roof slab (before and after backfill) to study the effect due to the backfill taking place around the model structure. Furthermore, the nuclear reactor enclosure of the JPDR has been instrumented with seismometers to measure vibrations of the structure and the ground

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[2] A bibliography listing such tests is found at the end of this paper.

during natural earthquakes. Results of measurements and calculations indicated that the structure's response was considerably influenced by the earthquake response of the surface soil layer.

2.3. Selected case studies

2.3.1. Case study no. 1. Containment building tests at HDR, Kahl, Fed. Rep. Germany

A series of ambient, forced vibration, snapback, and explosive tests were performed on the Heissdampfreaktor (HDR), a decommissioned nuclear power plant facility located in the Federal Republic of Germany [7,8]. 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 concerns were to identify the critical eigenfrequencies, modal deformations, and damping values of each structural system tested, and to compare the results with the analytical predictions of several independent groups using different computational methods.

The HDR containment structure consists of a cylindrical steel liner and a concrete outer shell. The structure is only slightly embedded in the soil. 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. The response of the structure to eccentric mass shakers at various locations was predicted prior to forced vibration tests.

Sinusoidal vibrators (up to 60 tons force), snapback (up to 10 tons force), and buried explosive charges (up to 10 kg) were used to excite the structure and several internal piping systems to provide estimates of dynamic properties. The first mode of the containment was found at 1.55 Hz with about 5% damping at 10^{-3} g and at 1.35 Hz with damping of 8% at 10^{-1} g. Piping was excited to several g's response and damping up to 10% was measured.

2.3.2. Case study no. 2. San Onofre primary coolant system studies, San Onofre, CA

Forced vibration tests [9–14] were conducted at the San Onofre Nuclear Generating Station Unit I reactor containment building and the primary coolant system during a refueling outage. Dynamic properties were identified and used to modify an analytical model. The San Onofre station has a spherical steel containment deeply embedded in the soil.

The analytical model was used to study the response of San Onofre to earthquakes. Test 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% damping at 10^{-3} g.

2.3.3. Case study no. 3. Equipment tests at Diablo Canyon, San Luis Obispo, CA

Vibration tests of equipment at the Diablo Canyon Nuclear Power Plant near San Luis Obispo, California, were performed for Pacific Gas and Electric Company [15]. These tests were part of a general review of the plant design required by new seismic design criteria. Extensive in-situ dynamic testing of the piping systems and safety related equipment was used to obtain experimentally validated dynamic models for extreme load design assessment. The resultant data allowed improvements to the theoretical models and a more accurate evaluation of the seismic capacity of the equipment, reducing the need for design changes. In most cases damping measured at allowable test excitation levels (<0.5 g) exceeded the suggested regulatory values. Thus, in situ testing proved to be an economical, rapid, and invaluable adjunct to engineering analysis.

2.3.4. Case study no. 4. KKP piping tests, Fed. Rep. 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 Phillipsburg (KKP), an 864 MWe nuclear power plant in the Federal Republic of Germany [16]. Testing was performed at the request of Technischer Uberwachungs-Verein (TUV) Baden e.V., Mannheim, which is the licensing aythority for this nuclear plant.

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

The purpose of the experimental study was twofold: (1) to provide a benchmark 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 piping systems.

The piping system at KKP was excited by snapback techniques to about 0.5 *g* while the response was measured and analyzed to yield estimates of resonant frequencies, mode shapes, and damping. The theoretically predicted first mode resonant frequency was 25% less than the measured value even after the 'as-built' conditions were incorporated into the theoretical model (a 50% difference existed when using the as-drawn model and specifications). The error was due largely to the actual system being stiffer than predicted. Damping in the lower six modes was higher than assumed in design (as much as 9% rather than the assumed value of 2%). Damping in higher modes was less (on the order of 2%). The two trends observed in the LDS piping system (increased damping and increased stiffness) tended to reduce earthquake response by a factor of two. Viewed in another sense, the tests demonstrated a seismic capacity equal to twice the capacity predicted by analysis alone.

2.4. Summary

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

- testing can be accomplished conveniently and quickly;
- testing is economical and safe;
- testing provides valuable information to confirm vital seismic design parameters; and
- testing yields insight into parameters which cannot be calculated, such as damping [17].

Confirming seismic tests of nuclear power plants in areas of high seismic activity would increase the reliability and accuracy of structural analysis methods which would lead to increased confidence in seismic analysis and design. 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 for the licensing review.

To date, dynamic verification tests have been carried out on more than 30 nuclear facilities world wide. All major systems and equipment have been tested without problems. The systems tested and the test methods are summarized in table 2. Based on the results of these tests it can be concluded that vibration testing of power plants is both useful and feasible.

Table 2
Previous experimental tests of nuclear power plant structures and equipment

ITEM	TEST METHOD*				
	sv	st	b	sb	a
CONTAINMENT BUILDINGS					
Steel, sphere	●				
Steel and concrete, cylinder	●		●		
Concrete, cylinder	●				●
Electrical penetrations		●			
PRIMARY COOLANT LOOPS					
Piping	●		●		
Steam generator (gas)	●		●	●	
Steam generator (water)	●				
Steam generator (sodium)			●		
Pumps	●		●		
Pressurizer	●				
REACTOR VESSELS					
Pressurized water reactor	●				
Boiling water reactor					●
Gas-cooled reactor	●		●		
Reactor core	●		●		
Reactor fuel element		●			
AUXILIARY EQUIPMENT					
Circuit breakers	●		●		
Transformer	●				
Emergency diesels	●				
Fire protection equipment		●			
Control panels	●	●			
Lightening arrester	●			●	
Capacitor banks	●			●	
Cable trays	●	●			
Cooling Towers					●
Tanks	●	●		●	

*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 (5), (18), (19)

3. Testing methods

3.1. Introduction

Several testing methods which have evolved in recent years would be sufficient to excite a nuclear containment structure so that the structure's dynamic characteristics could be identified [19]. Each method relies upon monitoring and analyzing the test structure's response to known forcing functions. These forcing functions arise from natural events, such as ambient vibrations, and applied loads such as impulses, sinusoidal varying loads, and randomly applied loads. The forcing functions may be categorized into three groups: those which are transient in nature, random in nature, and steady-state in nature.

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 discussed further 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 identifying structural modes not involving soil–structure interaction, damping, or other nonlinear phenomena.

The measurement of resonant frequencies, mode shapes and damping ratios is the primary goal of most testing regardless of the testing technique used. Usually testing is carried out with some initial idea 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 plays a role in the decision as to which testing method will be used.

3.2. Transient testing

Several methods can be used to cause transient response of structures. These include 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 allowing the structure to undergo free vibration with the initial displacement as the initial condition. This method has been used successfully to test large exhaust stacks [20], heavy equipment including steam generators [5], and piping systems [8].

A method of applying the force and a method of quick release are required. 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. Equipment for snapback testing is much simpler than that used for most other types of testing.

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. The snapback method would not be practical, however, for testing of a full-scale structure such as a reactor containment vessel.

In practice, it is sometimes difficult to isolate vibration modes of interest because the method tends to excite more than one mode at a time. Preanalysis 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 vibration modes of mechanical equipment and small buildings. By running with quick starts and stops, one individual can produce responses greater than the ambient vibration level in a 20-story building.

High level impulsive loading methods include the use of mechanical pulse generators and chemical rockets. Mechanical pulse generators produce force by drawing metal bars with variable cross sections through a cutting tool. 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 [21] and to test a 100 ton electrical panel [22]. Application to buildings is also being planned [23].

Chemical rockets produce forces by high velocity ejection of chemical matter. The chemical rocket is attached to the structure and the reaction to ejection transmitted to the structure. Types of propellants include hydrogen and oxygen as well as various solid materials. Large thrusts of 25 tons force and 0.5 s duration are attainable for single rockets. Larger durations of 20 s are possible but with lower thrusts. Rockets can be attached in parallel to produce larger total thrust [23,24].

Chemical rockets have been used in tower tests [25], but recent experience with chemical rockets for structural testing either in the laboratory or in the field is minimal. This lack of experience currently 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 used rockets to simulate aircraft impact. The rockets produced up to 10 tons force for 0.5 s. Up to four such units were used and fired simultaneoulsy. Compressed gas rockets have also been proposed for testing containments [23].

3.3. Buried explosives

The use of buried explosive charges has demonstrated promise for high level tests of full-scale structures and equipment. 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 nuclear power plant testing was in 1969 at the Enrico Fermi Power Plant [26,27,28].

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, were achieved. Buried explosives were also used in tests of a large nuclear power plant in Oak Ridge National Laboratory in 1970 [29]. During the Oak Ridge tests, up to one ton of dynamite was used as distances of 100 m 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 [30,31]. Test accelerations were proportional to $W^{1/3}$, where W is the charge weight. Other findings of this literature review were:

(1) the required depth of charge burial and crater size for specified ground motion would 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 versus undisturbed) is important.

A more recent review of the literature has been provided by Higgins and his associates [32]. 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.

Explosives have also been used in three other areas:

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

(2) creating specified (scaled) high-level ground motions for testing up to 1/8th scale nuclear power plant containment buildings [6]; and

(3) performing moderate level tests of a German nuclear power plant [8].

Other structures have been tested by explosives, including reactor piping systems, model buildings, and reinforced earth retaining walls [5].

Seismic simulation tests using buried explosive charges is a proven, viable technique. Large structures can be excited to peak levels of reponse ranging from $10^{-4}-10^{0}$ 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 so as to avoid ejection of soil and debris. Experience indicates that 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 meters of the tested structure.

In conclusion, it should be pointed out that use of buried explosive charges, more than any other test method, causes inputs most resembling actual earthquakes. The energy is transmitted through the soil to the foundation and all systems are excited (buildings and equipment).

3.4. 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 constant 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. With eccentric mass vibrators the force is produced by rotating eccentric masses about an axis. The force is changed by altering the eccentric mass (add mass, extend mass, or redistribute mass). The force can also be 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 3 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. Fig. 1 illustrates the nature of a large eccentric mass vibrator. The vibrators are driven by motor-controlled systems which are usually capable of maintaining the vibrator frequency within 0.1% of the desired value. An additional capability is an automatic sweep of select frequency ranges.

Linear hydraulic and electro-dynamic actuators are also used. 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. Eccentric mass vibrators usually require less input energy than linear hydraulic units since the flywheel effect of the former reduces the peak power required for control.

Sinusoidal vibrators, especially eccentric mass units, have been used in numerous nuclear power plant containment and conventional building tests. The techniques are well proven 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 to almost any desired level of response.

3.5. 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 is 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.

Table 3
Typical eccentric mass vibrators

DESIGNATION	MAXIMUM FORCE (NEWTONS)*	MINIMUM FREQUENCY FOR MAXIMUM FORCE (Hz)	UPPER LIMIT FREQUENCY (Hz)	MAXIMUM 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	5,300.0	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	1,500.0	~20,000	100.0

*4.5 NEWTONS ~ 1.0 lbf

Table 4
Typical electrical and hydraulic vibrators

DESIGNATION *	MAXIMUM FORCE (NEWTONS)	MINIMUM FREQUENCY 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 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.

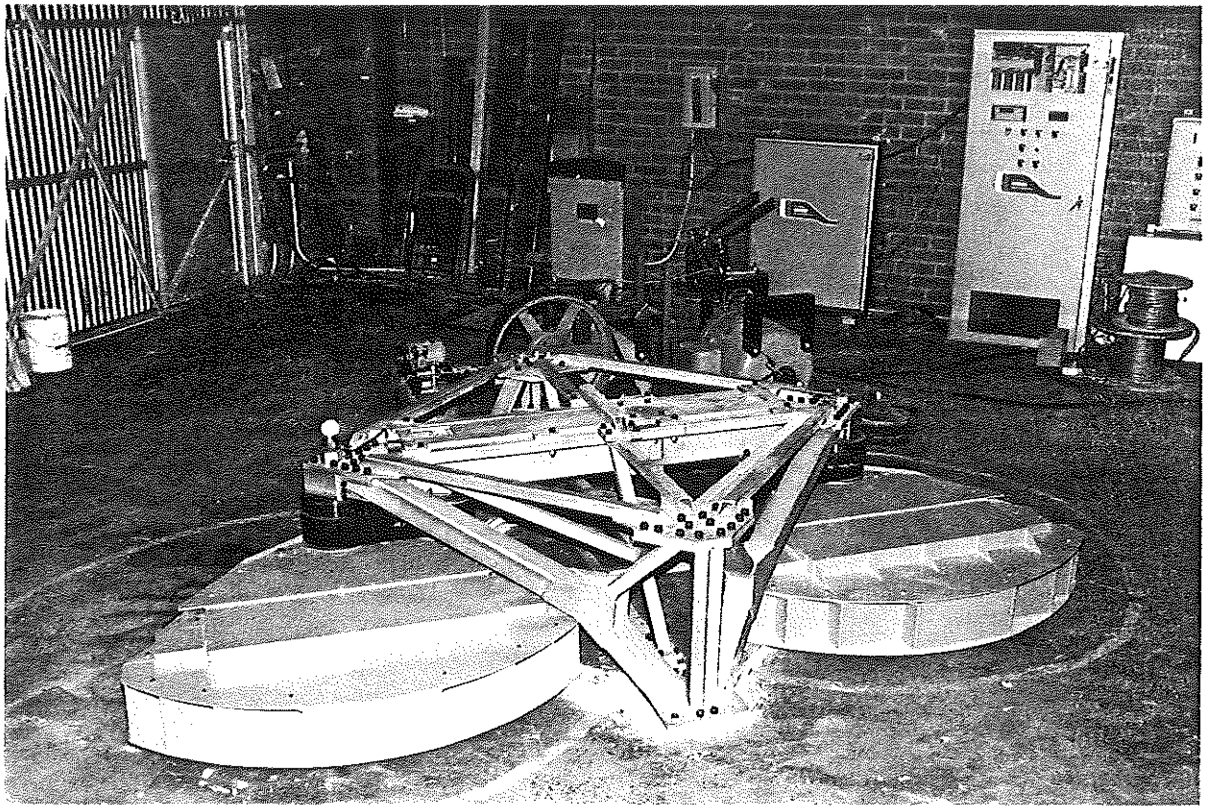

Fig. 1. Large eccentric mass vibrator (ANCO MK-15) (one of two dual units).

– All plant equipment is excited at the same time and this may be important for cases in which 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 to control.

– All equipment is excited; it is not possible to isolate and test just one component.

It is usually 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 itself is being tested, 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. 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, however, can be performed for more modest costs, as discussed elsewhere in this paper.

3.6. Summary

Mechanisms for transient response testing and for steady-state testing include snapback devices, mechanical pulse generators, rockets, buried explosives, and sinusoidal vibrators. One or more can 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, plant configuration, and site condition. A rating of each method for 11 test parameters is provided in table 5, for which it is assumed that a containment structure weighing 15 000 tons with 10% damping is to be tested.

A field proven method capable of high response levels is needed for practical seismic testing of nuclear power plant reactor containments. Sinusoidal testing and buried explosives are the most suitable, since they have been proven in the field and are both practical and economical.

4. Allowable levels of response

4.1. Introduction

The safety requirement for dynamic testing of a nuclear plant is straightforward: response amplitudes which might impair the licensability of the subject plant must be avoided. One may proceed through a series of steps of increasing analytical 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 amplitude acceptability one might consider:

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

(2) loads imposed on the specimen during 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 load 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 methods (step 5) to monitor and limit response amplitudes during testing, including strains at critical locations.

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 dissipation) that has been observed as a function of increased amplitude in piping systems, structures, and in soil–structure interaction [5]. Instead, conservative procedures are used which typically overestimate system dynamic response by underestimating damping in an equivalent linear model.

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, the authors' 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 the plant.

To date, plants under construction and commissioned and decommissioned nuclear power plants have been tested. 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 levels. Since cold plants typically have fewer loading conditions than hot plants, it is anticipated that the test levels could be larger for cold plants. Reduction in internal pressure, for example, results in lower stresses, permitting increased test stresses. An operating plant could impose an unacceptable 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 affect test results on the containment structure. Internal equipment such as piping with gaps and snubbers might be affected, but with due experimental consideration the 'hot' condition can be closely simulated.

4.2. Containment structures and internal equipment

For containment structures, dynamic test amplitudes have been restricted typically to much less than those that would be associated with a subject plant's OBE; this is desirable to eliminate serious con-

Table 5
Qualitative assessment of testing methods

CRITERION OR TEST OBJECTIVE \ EXCITATION TECHNIQUE	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	G	P	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	M	L	H	L	L	H	M	L

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

H = High
M = Moderate
L = Low

cern for Category III equipment. Peak response levels varying from 10^{-3}–10^{0} g are possible using sinusoidal forced vibration and buried explosive charges. Only when using explosive techniques or when using the largest vibrators available is there concern with excessive structural excitation.

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 conservative or that testing amplitudes will have no subsequent adverse impact.

The fraction of OBE response selected for testing should be plant specific. Plant sites with low OBE levels (e.g., 10% 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 erection loads might lead to several g's. These arguments would seem sufficient for justifying a significant fraction (say up to 100%) 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 test equipment to excite containment structures of all but the smallest of plants. During sinusoidal tests, however, a greater conservatism must be used than during explosive or other impulsive tests. This is necessary because the magnification above base motion for equipment in a sinusoidal test is proportional to Q, where $Q = 1/2\beta$, and where β is the fraction of critical damping of the equipment. For earthquake-like quasi-random motion, the magnification relation is somewhere between $\sqrt{Q}$ and Q [33]. This indicates an additional conservative factor of about $Q^{1/4}$. For 3% 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 adequate response margins for Category III equipment. Category I and II equipment are designed to tolerate repeated OBE loadings since the plant itself is required 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 site-specific Safe Shutdown Earthquake (SSE).

Cases may exist where application of the above conservative limit is not acceptable. That is, it may be desirable to excite the plant to higher response amplitudes to demonstrate high values of energy dissipation, keeping in mind the possible sensitivity of Class III equipment. 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 overemphasized 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 costeffective means of demonstrating continued Category III function.

An additional reason damage is considered unlikely until well in excess of the 0.1 g spectra ZPA limit is that vertical motion has not been considered in either testing or in actual capacity of the Class III equipment. This is because excitation equipment is typically designed for horizontal excitation; high level vertical excitation is difficult in the frequency range of interest. The fabrication and transportation 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 system's 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 for containment driving. For example, it is quite possible to directly excite a small diameter piping system beyond the ASME Code allowable with the application of a few tons of force in a snapback test.

4.3. Piping systems

In the past, tests have focused typically on the containment or on major piping systems (primary, secondary, emergency, etc.) and safety related equipment (e.g., diesel generators, control panels, and other equipment). Smaller piping systems and their associated equipment (steam generators, pumps, valves, supports and restraints) have also received major attention. Low level testing (loads of, say, one-half ton) has not presented safety concerns for piping systems larger than several centimeters or inches in diameter. Larger amplitude tests have received careful analysis by the applicable portions of appropriate codes, including for recently designed piping systems, such as 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) combination of the resulting loads in accordance with ASME Code equations pertinent to the particular system (ASME Class I or Class II);

(4) determination of the maximum allowable forcing from several such load cases; and

(5) specification of an appropriate test monitoring system to insure in real-time that acceptable test responses (e.g., stress or applied moments) are not exceeded.

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% of the stress limit in many piping systems.

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 1 (Subsection NB) and Class 2 (Subsection NC) piping 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 National Standards Institute, are calculated in a similar manner as above, but may result in substantially lower allowable test levels as older piping systems were usually designed to less stringent design standards. It is assumed here that any future test would use the current design methods to justify test levels.

5. Instrumentation, data presentation and parameter identification

5.1. Instrumentation

The experimental seismic evaluation of nuclear power plants requires instrumentation which can transduce, record, and analyze strain, relative displacement, velocity, and acceleration [1]. Several types of accelerometers are suitable, including strain-gauge bridge, piezoelectric, piezoresistive, and force balance types. Displacement transducers usually consist of a sliding arm on a variable resistor, a linear variable differential transformer (LVDT), or a linear variable capacitance.

A variety of signal conditioning pre-amplifiers, amplifiers, filters, etc., are available. Carrier or DC coupled amplifiers with balancing capabilities are used with strain gauges, strain gauge accelerometers, and strain gauge force transducers. Force balance accelerometers and other transducers are usually used by DC amplifiers. Filters are useful for eliminating noise, the effect of modes of vibration other than those under study, for baseline correction, and for preventing aliasing during digitization. A linear mixer, which adds or subtracts signals in a predetermined manner, is helpful for 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 ordinary spectra with either Fast Fourier Transform (FFT) routines or time compression/bandpass filtering techniques. Two-channel analyzers compute ordinary and cross spectra, transfer functions, and other statistical measures using FFT routines. The resulting spectra and transfer functions may be compared individually with analytic results, or digitized for more extensive comparisons.

In addition to general purpose analyzers, several companies have produced minicomputer-based systems for excitation, data acquisition, data 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 [19].

In summary, vibration transducers, instrumentation, and computerized data analysis systems have been evolved and assure that, with care in system design and specification and with experienced use, all data acquisition goals of a test program can be met. Instrumentation and data acquisition are not limiting factors in testing [1,19,34,35].

5.2. Data presentation

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

Data should be taken in situ in digital form; however, analog 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. Eventually all data should be put into digital form and 10–20% 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., ASCII magnetic tapes).

5.3. 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 vibrators 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. Most likely only preliminary simple parameter identification need be performed in the field. Subsequent parameter identification on the acquired data base would be conducted during post-analysis.

Parameter identification techniques can be divided into two groups: (1) eigenparameter identification – techniques which can be used to estimate resonant frequencies, damping, and mode shapes from experimental data; (2) model modification – techniques which can be used to modify the mass and stiffness properties of structural models given the experimental estimates.

Eigenparameter identification techniques typically use a linear combination of single-degree-of-freedom response curves to fit the data [19,36]. Parameters such as resonant frequencies and damping are varied to reduce the difference between data and theory and to find the 'best' parameters. One step estimation procedures are also available [19,37]. These techniques can also be categorized by their operation on data in the time domain or frequency domain (Fourier transform on sinusoidal data). Certain methods have been developed for handling nonlinear model parameter identification, but they have not been used extensively in practice.

Once the eigenparameters are estimated, the analyst may ask "How should I change my model to reproduce more closely the experimental data?" This can be accomplished by simple heuristic 'trial and error' methods or by more sophisticated mathematical techniques. Of the latter techniques, Bayesian identification is particularly powerful [19].

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 minimum 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. Bayesian techniques have been used in optimizing models of aerospace structures, offshore oil platforms, and nuclear power plant containment and piping systems.

In summary, 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 curve fitting or one-step routines should they prove suitable with typical data (the least-mean square techniques have been proven 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 be used with nonlinear model properties.

6. Extrapolation of damping at higher than achieved response levels

6.1. Containment structures

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

(1) structural deformation, and

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

Fundamental mode damping data obtained from full-scale tests and model tests are summarized in table 6. The total apparent damping is reported; separate effects of structural deformation and soil–structure interaction have not been obtained, however, although techniques are available to perform this separation.

Forced sinusoidal vibration tests with 35 tons force of the Tokai-2 containment building resulted in a peak acceleration of 10^{-3} g on the operating floor 35 meters above the ground. The estimated damping of the first (rocking-translation) mode was 15–20% [38]. Damping in the higher modes was estimated to be 8–15%, the lower damping values associated more with structural deformation than with soil–structure interaction. Typically, 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 = 1 000 m/s) and the CVTR (a concrete containment in a softer soil) were both tested at 10^{-3} g response amplitude. The estimated damping for the EGCR was 2–3% and the estimated damping for the CVTR was 6% [39,40,41]. These and other test data suggest that concrete containments at soft sites are characterized by higher damping than are steel containments at stiff sites. Higher level tests [5] suggest that a damping values of 15–20% is representative of concrete containments and soft sites.

Test results also suggest that the damping (energy dissipation) 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 5 tons. This resulted in an amplitude response of one milligee and an estimated 16–18%

Table 6
Summary of measured damping in containments

NUCLEAR PLANTS	ESTIMATED DAMPING (Percent of Critical)
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% at ten milligees, blast testing
CVTR (Parr, South Carolina)	6% at one milligee, forced vibration testing
Enrico Fermi-I (Monroe, Michigan)	6% at ten milligees, blast testing
Tokai-2 (Japan)	15% or higher in fundamental mode at one milligee, higher modes involving concrete deformation were 8 to 15%, forced vibration testing
Hamaoka (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
HDR (Near Frankfurt, Germany)	5% at one milligee, 8% at 0.1 g, forced vibration and blast testing

damping [5]. These damping estimates may be compared to 20% damping 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 2–3%. Blast testing resulted in response amplitudes of 10 milligees and a damping of 3–4%.

Increased damping with increased response amplitude has been observed in other full-scale tests [5] and in model tests [6]. The relationship between the response amplitude and damping, however, is nonlinear and extrapolation of damping at higher response levels would require several intermediate level tests.

6.2. *Internal equipment*

Considerably more data are available on equipment damping and have been summarized in refs. [42] and [19]. As indicated in the following two case studies, taken from [19], damping is generally higher than regulatory values at reasonable test levels and typically increases with increasing response. Some damping measurements at Diablo Canyon [15] on a 12.5 cm (5 in) pipe indicated a high damping of 16% at 0.01 *g*, lower damping of 5% 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. No data have come to the authors' attention that indicate that damping will decrease above about 0.5 *g* response in nuclear power plant equipment. There is some concern, however, as to how to define a linear equivalence to the increasing and nonlinear energy dissipation that is typical in such equipment above 0.5 *g* response.

6.3. Selected case studies

6.3.1. Case study no. 1. Damping measurement on a pressure vessel model

A model of a typical reactor component was built (see fig. 2) for use in dynamic studies. The amplitude of the initial displacement was varied and damping estimated from measured free vibration traces. The system was excited in free vibration using snapback techniques. The system resonant frequency was about 6.1 Hz. Damping was obtained from the acceleration records using the logarithmic decrement method.

The graphical results in fig. 3 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

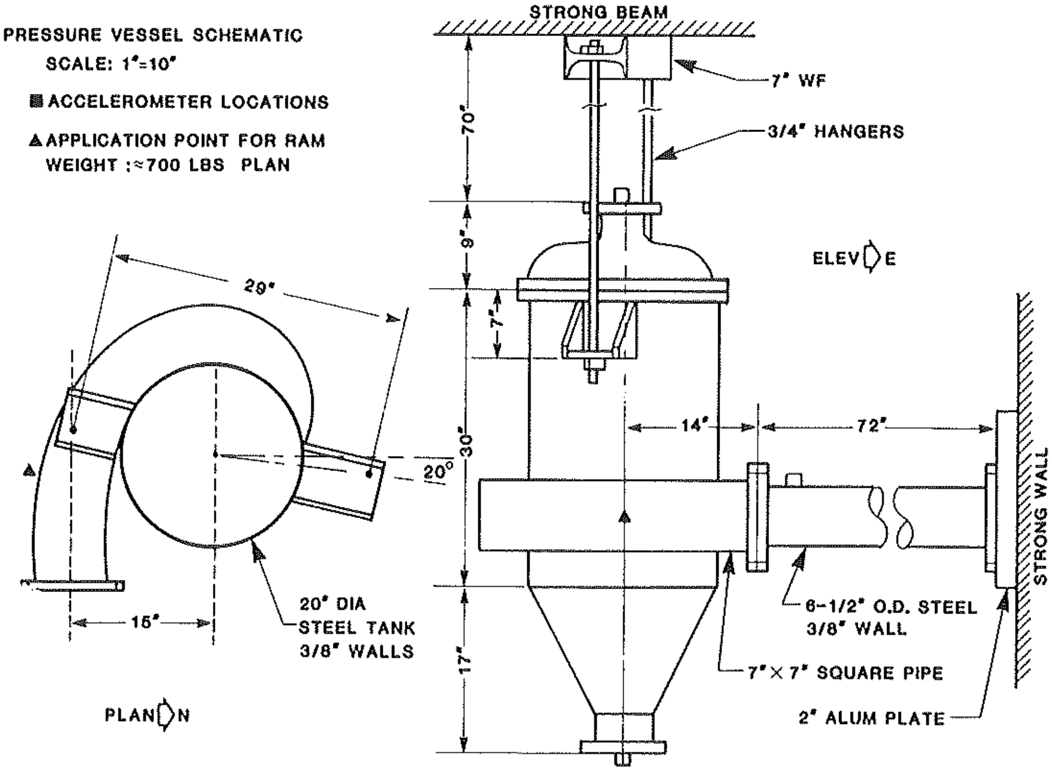

Fig. 2. Plan and elevation of laboratory test structure.

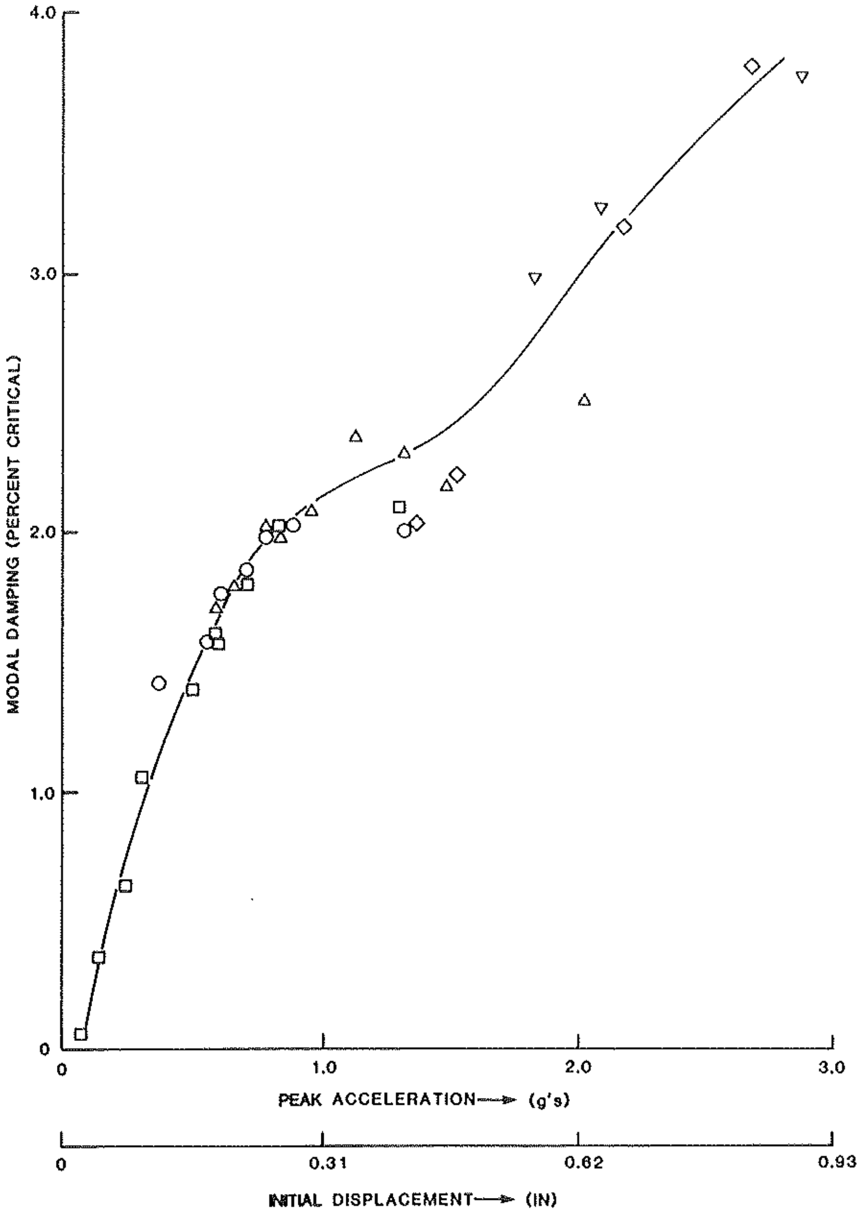

Fig. 3. Damping versus response amplitude.

experienced some yielding when the initial static displacement was greater than approximately 3 cm (1.2 in). The scatter in the damping values in this range seems to indicate such a system change.

6.3.2. Case study no. 2. Damping estimates on pressure vessel systems

Currently the damping values accepted for use without proof in the dynamic analysis of nuclear power plants are specified by NRC Regulatory Guide 1.61, as shown in table 7. Values are in percentage of critical damping.

The experimental data on pressure vessel systems indicate that the regulatory values are somewhat low. Table 8 summarizes many of the experimental damping studies discussed in the text and indicates that

Table 7
NRC 1.61 Regulating Guide damping values for components and structures

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

Table 8
Summary of measured damping in piping

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	C" dia pipe	1.00	4.0	1.0

the allowable OBE values are equal or exceeded even at low response levels ($<0.10\ g$). Since experimental data suggest that damping increases at higher response levels, it would appear that regulatory values are low by a factor of 50–100%, at least. In selected cases the regulatory values are low by several factors.

7. Plans for testing a typical plant

7.1. Introduction

The planning and data analysis 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 two principal horizontal directions and the dynamic properties of selected internal equipment.

7.2. Pre-test analysis

Pre-test analysis involves the creation of an a priori analytical model of the reactor containment building (RCB). The analysis would aid in determining: (1) the optimum location and 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, and time and frequency response) via the development of a simple 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 are difficult to linearize, but are found not to have significant effects on the global modes of vibration of containment structures. 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 and thus invalidate the 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 an existing power plant. Therefore, it is possible that dynamic modeling and analysis were accomplished during the plant's seismic design phase. 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.

7.3. Test plan

The test plan contains detailed information about the proposed tests on a test-by-test basis and a specific schedule of events, and would include the following information:

(i) Stated objective of each test.

(ii) 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.

(iii) Relative magnitude and direction of applied force referenced to some global coordinate system.

(iv) 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.

(v) Schematic drawings specifying the type and location of transducers and details for instrument mounting and orientation.

(vi) The exact nature of the test environment. For example, if a piping system is being tested the pressure and temperature would be specified, and its water content and support system verified.

(vii) The required test results must be clearly stated, including:

identified resonant frequencies,
estimated damping values,
identified mode shapes,
frequency response data,
achieved response levels,
time history data.

(viii) The format for the presentation and organization of acquired data would need to be specified, including:

tabulation of natural frequencies,
tabulation of model damping values,
digital computer tape of response,
plots of response,
Fourier transform of transient response,
mode shape plots,
movies,
photos.

7.4. Post-test analysis

In the post-test analysis phase, the analytical model and test data are 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 analysis results and test results. This phase involves:

(1) detailed analysis of the test data;

(2) assessment of test data reliability;

(3) assessment of uncertainties in model parameters; and

(4) tuning of model parameters using parameter identification.

The detailed data analyses include: (1) generation of steady-state response amplitude versus vibrator excitation frequency plots 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. Mode shapes would be determined from the transfer function of the acceleration responses (amplitude and phase) at various locations and with given applied forcing using model parameter identification techniques.

The reduced test data are compared with the structure's analytical model to refine the structural stiffness, mass, and damping parameters. For this purpose the Bayesian identification technique previously discussed would be used.

7.5. Scheduling and costs

The time and costs required to perform a test depend on the test's scope and objectives. 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, approximately 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 US dollars. The large test program would answer questions regarding the plant dynamics, 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 several weeks of testing. Many possibilities exist between these two extremes.

For budgeting and scheduling a typical program, 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}–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: a loop of the primary coolant system and the polar crane. The authors 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 components include a manpower effort of approximately 7 000 hours plus additional direct costs of approximately US $ 200 000. The tasks required by this example make the test very detailed, involving a fair amount of preparation, testing and data reduction. The pre-test analysis would require about five months, the testing about two months, and the post-test analysis (to final report) about three months. These numbers are estimates only and could easily vary by ±50% depending on the specific requirements of the project.

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