NUREG/CR-3892
Vol. 1

A Research Program for Seismic Qualification of Nuclear Plant Electrical and Mechanical Equipment

Part I: Survey of Methods for Equipment and Components
Part II: Evaluation of Methodology
Part III: Qualification Methodology for Line Mounted Equipment

Prepared by D. D. Kana, E. Z. Polch, D. J. Pomerening, J. C. Simonis, J. F. Unruh

Southwest Research Institute

Prepared for
U.S. Nuclear Regulatory
Commission

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NRC FIN B7087

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SURVEY OF METHODS FOR SEISMIC QUALIFICATION OF NUCLEAR PLANT EQUIPMENT AND COMPONENTS

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Report No. SwRI 6582-001-01
Contract NRC-04-81-185
Task 1 Summary Report Part I

Prepared for
U. S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, D. C. 20555

October 15, 1982

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1.0 ABSTRACT

An extensive review of methodology for seismic qualification of nuclear plant equipment is presented, and some associated anomalies that can effect the results are identified. Emphasis is on qualification by testing, although some information on all currently-used methods is also included. The contents are intended to complement those of other recent review efforts which have emphasized evaluation of analytical methods.

A brief historical overview of equipment qualification efforts is described, and a list of equipment under consideration is presented. Eleven groups including thirty-one subgroups are identified. A summary of equipment description, typical mounting, seismic qualification methods, failure modes, and other information is given for each equipment subgroup. Typical qualification methods that have been used from the past to the present are identified, but it is found that more than one method may have been applied for qualification of different specific hardware that falls within a common subgroup. As a result, it is recommended that comparisons be developed for the identified methodologies regardless of which subgroup to which they have been applied. Such comparisons are essential for evaluation of the validity of earlier simpler tests, compared with more recent complex requirements.

Various anomalies associated with qualification by testing, analysis, and combined test and analysis are identified. A description of continuing research efforts intended to alleviate some of the anomalies are given, along with recommendations for further work to shed light on the others.

2.0 INTRODUCTION

2.1 Overview of Qualification Review Efforts

The need to design nuclear power plant equipment and buildings to withstand an earthquake has long been recognized, even in the first commercial designs. At first, seismic requirements were placed only on buildings and very selective pieces of equipment. Later the requirements were broadened to include almost all equipment. The first major design effort to construct a complete nuclear power plant and its equipment to withstand an earthquake was for San Onofre Unit I in 1968. Today all nuclear power plants undergo very rigid evaluation for their ability to withstand a site specific earthquake. Past and present techniques used to evaluate the seismic adequacy of nuclear power plant equipment are a focal point of technical research and scrutiny. Examples of the present attention being given to seismic equipment design can be obtained from various NUREG reports which review the seismic qualification of specific equipment [Refs. 087, 274, 275, 277, 308].

The Electric Power Research Institute (EPRI) sponsored a study by Howard, et al[020] for an overall review of the seismic design procedures used until 1977. In this report he evaluated some of the fundamental assumptions used in seismic analysis and concluded with recommendations for additional research needed to support analytical activities. The recommendations focused on response spectrum, damping and testing. The review and recommendations were bolstered by a survey from 13 respondents involved in the seismic design, analysis, and qualification of nuclear power plant equipment. The total number of questionnaires distributed was 40.

The recommendations in Howard's review emphasized the need to experimentally verify the analysis associated with a seismic qualification of components and to include realistic conservative assumptions in the analysis. To achieve these recommendations he advocated in-situ testing of structures or the equipment which required seismic qualification, and deletion of the unjustified conservatism introduced into nearly every element of the design process. He felt that ultimately the conservatisms were compounded needlessly in the final design.

In addition to Howard's general review, other reviews have been published on the seismic design and qualification of equipment. These documents have identified many of the same needs as Howard's. The Institute of Environmental Sciences published in 1978 a compendium[204] of papers discussing the problems involved in the design and testing of equipment to resist an earthquake. This document provides a reasonable single source of information to understand past programs for seismic qualification, understand weakness in present qualification methodologies, and identify future qualification techniques which will emerge from research. Various other recommendations for changes in equipment design criteria have also been given by Coats, et al[273].

The most recent review of equipment seismic qualification methodology has been compiled by Kennedy, et al[087]. This is a very comprehensive and useful document which touches on many significant areas of the qualification problem. It begins with a classification list of subsystems and equipment by seismic qualification and response characteristics, a very important step in defining the extent of the qualification problem. A general description of both analytical and test methodology is included. Then, much detail is given in the evaluation of analytical methods, uncertainties in their use, and recommendations of computer programs and specific techniques for given equipment and subsystems. However, only a rather cursory coverage of similar methodology for qualification by testing is included.

In effect, the purpose of the present review is to extend the compilation of information provided by Kennedy, et al[087]. Some expansion of their original equipment list is included to allow easier reference to equipment assembly and device qualification methodology. Additional coverage of analytical techniques is included along with an overall discussion of the technical and legal demands for seismic qualification. However, the most important purpose of the present review is to provide much more complementary detailed coverage of test qualification methodology. This is accompanied by an extensive bibliography of reports and technical papers which deal with the subject.

2.2 Scope of Present Review

Since 1971, methods for seismic qualification of equipment have rapidly evolved from rather simple approaches to quite complex investigations which demand thorough evaluation of every structural subsystem and component in a nuclear reactor system. The growth in the requirements for seismic qualification of equipment in this 10-year period has been paralleled by the growth of a whole library of industry standards, regulatory guides, and interpretations, which govern the requirements for safe nuclear power plant operation. Even today through continuing efforts to improve equipment qualification procedures, we are finding new experimental and analytical techniques which will form the bases for future qualification technology.

In all this rush of development, it is appropriate to pause at this point, review the progress achieved, and map directions for continued development. Therefore, the purpose of this survey is to evaluate test and analytical methods, both past and present, for seismically qualifying the operability of mechanical and electrical nuclear power plant equipment. To accomplish this purpose, the following objectives were established:

1. Review and summarize existing methods of seismic qualification, with acknowledgement of other recent review efforts where appropriate.
2. Include other environmental factors only as a secondary consideration of how they affect results of seismic qualifications.
3. Describe the implementation of present seismic component qualification guidelines.
4. Generate a list of technical anomalies and deficiencies inherent in the present methods for seismic qualification of equipment and components.
5. Prioritize the technical anomalies and deficiencies identified in Objective 3, and then identify those items for which immediate research must be performed.

After completion of these four objectives, additional phases of the current research and development effort will be conducted to shed light on the identified needs.

The background of experiences from which the present review information was drawn includes several sources. Specifically it is based on:

1. An evaluation of publically disclosed reports and technical papers.
2. Verbal discussions with individuals actively qualifying equipment for nuclear plants.
3. Interaction with members of the IEEE 344 committee on seismic qualification of equipment.
4. Participation in NRC, industry, and technical society meetings on equipment qualification.
5. Active participation in equipment qualification programs for industry.

The review excludes evaluating techniques which:

1) predict soil structure interaction between the earth and building basemats.
2) acquire response data during an earthquake at operating nuclear plants or those under constuction,
3) predict the propagation of a shock wave from an earthquake epicenter to a building basemat, and
4) predict the maximum earthquake expected at a particular site based upon geological, historical or previously reported earthquake data.

Each of these four areas is also important for answering the ultimate question, "Is this equipment seismically qualified for a given site?" Individually, however, these four areas require separate studies and are therefore excluded from the scope of this review.

2.3 Categorization of Equipment and Components

The approach used herein for presentation of specific information catalogs the equipment into eleven (11) generic groups, subdivides these groups into logical subgroups and, then summarizes pertinent data for each of the subgroups of equipment. Generally, the generic groups fall under the categories of building substructures, electrical and electronic equipment, and mechanical equipment. The equipment subgroups generally follow the categories originally established by Kennedy, et al

[087], except that some expansion has been included to allow easy reference to qualification of assemblies and devices individually, and inclusion of additional equipment. Table 2.3-1 is a summary of this categorization, and includes a cross-reference of item numbers for corresponding equipment listed in Table 2-1 of Ref. [087]. For convenience, a copy of the latter table is included in section 9.0 of this report. Much more specific information about qualification of each equipment category is summarized in Section 4.0.

Information for the present review has been generated from a vast amount of literature. However, some of the references are more important than others. Therefore, the literature in Section 8.0 is divided into two parts; the first contains references of most value, and the second contains references which are only of further interest on the subject. References that provide information about qualification of specific classes of equipment will be listed in the respective category summary in Section 4.0. Furthermore, the most pertinent references are noted with an asterisk ( )* in that section. All references listed in Section 8.0 are available in publically disclosed literature. Unfortunately very few test reports on actual items can be included, since such reports are generally classified company proprietary.

2.4 Typical Plant Description

In order to establish the general environment in which nuclear plant equipment must operate, a brief description of typical plant operation principles will be given. Any loading which results from this operating environment generally must be included in seismic qualification procedures.

Reactors used for the commercial production of electrical energy use fission reactions in the core area surrounded by the reactor vessel which is located in the containment building. The heat generated by the reaction is removed by a fluid. Most U.S. commercial reactor systems use treated water for removing the heat produced by the nuclear reaction from the core. However, other media are also used for heat transport; for example, gas, sodium and deuterium oxide (heavy water). These other fluids have found little commercial application in the United States. Reactors in the U.S. using water to transport heat from the core are

TABLE 2.3-1 EQUIPMENT AND COMPONENT CATEGORIZATION

Generic Group	Generic Subgroup	*Correlation to Ref. 087
Electric Equipment Mounts	Panels	23
	Racks	23
	Cabinets	23
Electrical Instrument and Devices	Transducers Including Integral Signal Conditioners	23
	Computer Systems	23
	Communication Systems	23
Electrical Power Devices	Switch Gear	22
	Transformers	23
	Invertors	23
	Emergency Diesel Generators	20
	DC Power Limiters, eg. Batteries, etc.	21
Valves	Large Power Operated Valves Air or Electric	15,17
	Relief Valves	16
	Check Valves	16
	Instrumentation Valves	17,18
Piping	Large Pipes	5
	Small Pipes	6
	Buried Pipes	11

---

*See Section 9.0, Appendix.

TABLE 2.5-1 EQUIPMENT AND COMPONENT CATEGORIZATION (Cont'd)

Generic Group	Generic Subgroup	*Correlation to Ref. 087
Pumps	Main Coolant Pumps	12,13
	Medium to Large Pumps and Compressors	13
	Safety Related Pumps	12,13,14
Heat Removal Systems	Heat Exchangers	--
	Steam Generators	--
	Emergency Pump Drive Systems	--
	Large Cooling Fans, Motors and Generators	19
Air Conditioning Systems	Air Ducting	25
	Air Conditioning and Filtering	--
System Support Facilities	Cable Trays	24
	Fuel Storage Racks	--
	Reactor Containment and Facilities Building	--
	Internal Reactor Structures	2
Vessels	Large Vertical Vessels	7,8
	Large Horizontal Vessels	9,10
	Reactor Coolant Systems	1
Miscellaneous Components	Snubbers	--
	Fuel Rod Assemblies	3
	Control Rod Drive Mechanisms	4

---

*See Section 9.0, Appendix.

divided into two classes; boiling water reactors (BWR) and the pressurized water reactors (PWR). The BWR and PWR reactor systems are different in design. However, the portion of the nuclear power generation station outside the containment is similar, and often resembles the system used to generate electricity for conventional fossil fuels.

Figure 2.4-1 is a schematic diagram for a typical BWR system. In this system fluid is pumped into the core where it is heated. The water is allowed to boil and flash to steam as it passes through the core. The wet steam leaves the reactor area and passes through a series of devices called separators and dryers which remove the moisture from the steam. The dry steam then flows through the turbines. Once the steam has passed through the turbine it is returned as water to the reactor system.

Figure 2.4-2 is a schematic for a typical PWR system. This figure shows the primary and secondary systems. The primary system contains the reactor, the steam generator, and the pump. The secondary system contains the turbine, and its associated equipment. Water is circulated in this primary system by a series of pumps. The water enters the reactor system and passes through the core where it is heated to over 600° before it exits the reactor. During operation the pressure in this system is maintained at approximately 2200 psi to prevent this water from flashing to steam. The water exits the reactor and passes through the steam generator where it is separated from the secondary fluid by thin walled tubes. As the water passes through these thin walled tubes in the steam generator, the secondary fluid is heated to approximately 600°F and the pressure is maintained at approximately 1000 psi to permit the secondary coolant to flash to steam. Steam from the steam generator is used to drive the turbine and associated equipment in the secondary system.

Reactor systems, whether PWR or BWR, are housed in massive concrete and steel buildings called the containment. Most modern reactor containment buildings are concrete with reinforcing steel used to provide the necessary tensile strength. The reinforcing steel can be placed in the concrete with no prestressing in which case the building is called reinforced. Or the reinforcement steel can be prestressed in

Nuclear Engineering International
September 1980, Vol. 25, 303 p.45

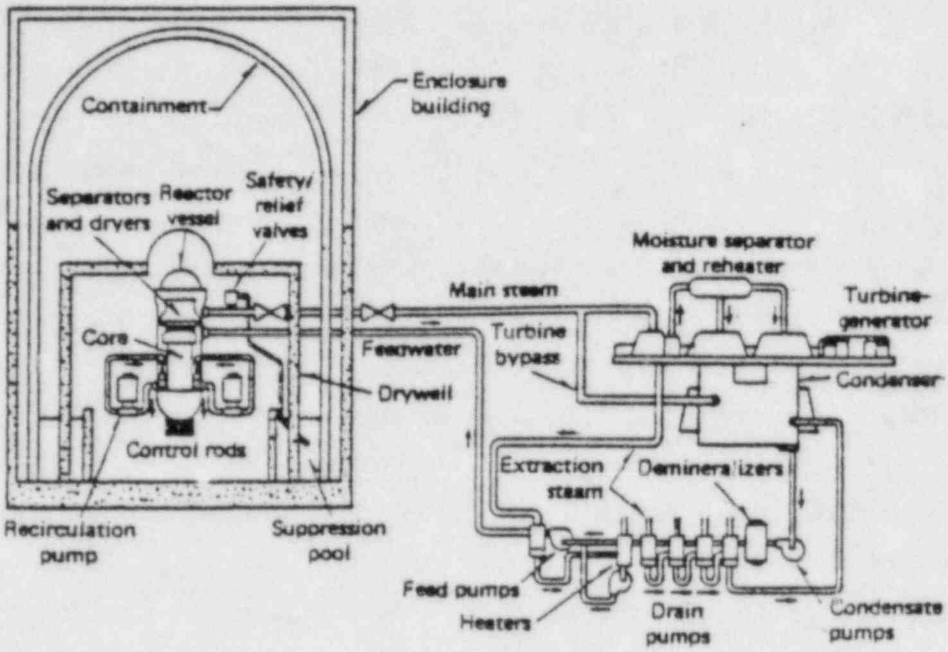


Figure 2.4-1 Typical BWR System

Nuclear Engineering International
April 1970, Vol. 15 No. 167, p.340

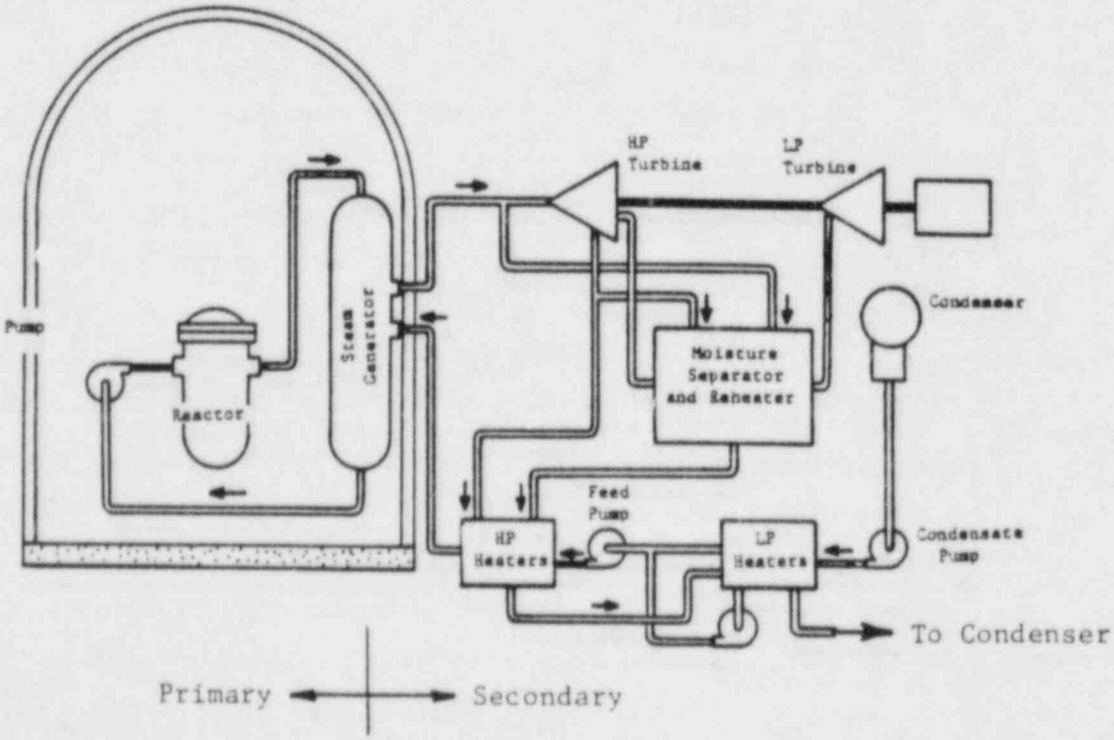


Figure 2.4-2 Typical PWR System

which case the building is called prestressed. In addition to these two types of containment buildings, a limited number have an internal free standing, thin shell-like structure which is surrounded by the concrete containment structure. All three types of containment buildings are currently used in operating nuclear power plants.

A complex array of instrumentation is necessary for the operation of nuclear power plants. Instrumentation systems can be functionally categorized as protection, control, or monitoring. Each of these systems may provide information which is necessary for the safe operation of the nuclear power plant. The protection system derives signals directly from a variety of protection variables necessary to safeguard the plant. Protection is provided for various classes of accident conditions, independent of the initiating cause. Measurements, for example, of pressure, flows, levels, and secondary plant parameters, and many other variables are used to protect the reactor system during accident conditions. From this diversity of measurement variables, the operator is furnished with information on the plant status. Also, these protection channels provide information on the status for various components.

Reliability is the utmost design goal for a nuclear reactor system. Generally the electrical and physical design of the protection system is based upon a channelized concept. In this concept redundant components and channels are maintained separate and distinct from one another. Often the protection system is composed of two parts: the analog or process measuring channels and the digital or logic actuation channels.

For the analog portion of the system, separation between redundant channels begins at the sensor and is maintained even through the instrumentation racks which the process signals pass. Redundancy is complete to both separate wiring, trays, conduits, power supplies, and other peripheral needs of a given sensor channel. Redundancy is enforced in the signal conditioning equipment. This equipment is located in separate racks, fed from separate vital electrical busses.

For the logic train portion of the system, information is accepted from various analog sensors. Logic devices perform the required functions which are necessary to safeguard the plant and actuate the appropriate safeguard systems. These actions are in the form of operating pumps, valves, breakers, and a variety of other necessary equipment.

There are many non-vital control functions associated with auxiliary and supporting systems of a nuclear reactor system. Reactor power is controlled in both the BWR and PWR plants by moving control rods. These control rods govern the rate of the reaction and hence the temperature associated with this reaction. Temperature set points are programmed functions of the turbine mode. For optimum control, temperature information is made available to the controller. Nuclear reactivity rates are involved in the feedback loop for maintaining stability. For a PWR the pressurizer is maintained at a fixed value by a closed loop control system which operates the pressurizer heater, spray valves, and relief valves. For a PWR system the water inventory in the pressurizer is controlled by forcing changes in pump flow. This water level is programmed as a function of the reactor coolant temperature and pressure. Under normal operation the steam generator feedwater flow is usually controlled using steam flow, feedwater flow, and steam generator water level to maintain the desired necessary water inventory in the steam generator. Reactor coolant temperature is used to prevent the addition of large amounts of sub-cool fluid. Steam bypass to the condensers removes excess heat from the reactor coolant system following a large load decrease or a plant trip. Steam bypass is normally controlled by the reactor coolant temperatures, but can also be controlled by pressure at other sources. Steam relief valves upstream of each steam line isolation valve are controlled by individual steam line pressures to prevent system overpressure.

The turbine generator instrumentation and controllers include the turbine control, turbine generator protection system, and the turbine generator supervisory instrumentation. The turbine generator protection system automatically trips the turbine generator in the event of an unusual condition. The supervisory instrumentation monitors the status of the various parameters associated with the operation of the turbine. These parameters provide an indication for the operating status of the generator and actuate alarms which enable the operator to manually evaluate the performance of the generator system. In addition to the protection and control systems, numerous monitoring systems are associated with the operation of a nuclear power plant. Generally these monitoring systems are in place only for information which could be needed by the operator. They provide no control but only routine status information.

3.0 GENERAL APPROACH TO QUALIFICATION

3.1 Need for Component Qualification

3.1.1 Technical Considerations

The need to consider the influence of an earthquake and other dynamic environments in the design of buildings and included equipment has grown from the earliest documented technical considerations. Generally, the path of development has been one where the discovery of new technical knowledge and understanding has led to revised quantification of codes and standards by technical society committees, and then to regulations and laws by governmental bodies, since public safety and property is inevitably involved. At first these codes dealt with conventional structures and facilities only. With the advent of nuclear power plants, greatly expanded magnitudes of potential public hazards were introduced because of coupled seismic and nuclear dangers. Rapid expansion of technical standards, codes, and regulations have occurred to formalize the process of component qualification, and to implement new knowledge. As new knowledge develops, it can be used to refine standards and codes, reduce uncertainties, or demonstrate margins in past and present practices.

3.1.2 Legal Regulations and Technical Standards

The birth of seismic qualification regulation as we know it today was in the 1975 Code of Federal Regulations, part 50, entitled "Licensing of Production and Utilization Facilities," Appendix A. The section in this document entitled "Design Bases for Protection Against Natural Phenomena" states:

> "Structures, systems and components important to safety shall be designed to withstand the effects of natural phenomena such as earthquakes, tornadoes, hurricanes, floods, tsunami, and seiches without loss of capability to perform their safety functions. The design basis for these structures, systems, and components shall reflect:

> (1) appropriate consideration of the most severe natural phenomena that have been historically reported for the site and the surrounding area, with sufficient margin for the limited accuracy, quantity, and period of time in which the historical data have been accumulated,
>
> (2) appropriate combination of the effects of normal and accident conditions with the effects of the natural phenomena, and
>
> (3) the importance of the safety functions to be performed."

This same appendix emphasizes the requirements for a test program to qualify equipment. This licensing document states, in part: "where a test program is used to verify the adequacy of a specific design feature in lieu of other verifying or checking processes, it shall include suitable qualification testing of a prototype unit under the most adverse, design conditions. Design control measures shall be applied to items such as the following: reactor physics, stress, thermal, hydraulic, and accident analyses; capability of materials; accessibility for in-service inspection, maintenance, and repair; and delineation of acceptance criteria for inspections and tests."

Prior to the establishment of this Federal regulation in 1975, industry standards for seismic qualification of electrical equipment had been generally adopted. Between 1971 and 1975 the Institute of Electronics and Electrical Engineers (IEEE) Standard 344-1971, "Seismic Qualification of Class 1 Electrical Equipment for Nuclear Power Generating Stations," was the basic guideline for seismic qualification. In 1975 this standard was extensively revised and represents the current governing guidelines. Nevertheless, as a directive from the IEEE Nuclear Power Engineering committee, this standard is today being reviewed and revised by the IEEE 344 committee, and a revision probably will be issued in 1983.

Thus, the IEEE standard 344 has guided the seismic qualification of Class 1E equipment in nuclear power plants for the last 10 years. This guidance has been recognized by its endorsement (with exceptions) in 1974 by the Nuclear Regulatory Commission (NRC) and their

Regulatory Guide (RG), 1.10 entitled "Qualification of Class 1E Equipment for Nuclear Power Plants." In accepting this standard the NRC noted:

> "the procedures described in IEEE standard 323-1974, 'IEEE Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations' dated February 28, 1974 for qualifying Class 1E equipment for service in light water-cooled and gas-cooled power plants are generally acceptable and provide an adequate basis for complying with the design verification requirements of Criteria 3 of Appendix B to 10 CFR, Part 50, to verify the adequacy for design under the most adverse design conditions."

In addition to the previously-mentioned documents which provide general guidance for the seismic qualification of Class 1E electrical equipment, numerous other NRC and IEEE standards have been developed for specific equipment or uniquely located equipment. Table 3.1-1[284] lists additional NRC Regulatory Guides which can provide guidance for various types of seismic qualification. Some of the identified documents provide specific guidance, while others only infer guidance. In addition to these regulatory guides, the NRC is currently developing other guidelines on the environmental qualification of equipment important to safety in mild and harsh environments.

IEEE Nuclear Standards which specifically require seismic or vibration qualification of equipment are listed in Table 3.1-2. These standards often infer seismic testing requirements by referencing specific standards on seismic qualification. The listed standards blanket many categories of electrical equipment used in nuclear power plants. This list does not include all of the standards that can be invoked for seismic qualification of equipment, but is a representative one.

3.2 Methods of Seismic Qualification

This section presents a brief overall description of the techniques used to qualify equipment. Additional general information can be obtained from the review presented by Kennedy, et al[087]. Three

TABLE 3.1-1 DIVISION 1 REGULATORY GUIDES, POWER REACTORS

Number	Title	Rev.	Issued Year/Month
1.9	Selection, Design and Qualification of Diesel-Generator Units Used as Onsite Electric Power Systems at Nuclear Power Plants (For Comment)	---	71/03
		1	78/11
1.11	Instrument Lines Penetrating Primary Reactor Containment (Safety Guide 11)	---	71/03
	Supplyment to Safety Guide 11, Backfitting Considerations		72/02
1.12	Instrumentation for Earthquakes	---	71/03
		1	74/04
1.13	Spent Fuel Storage Facility Design Basis (For Comment)	---	71/03
		1	75/12
1.18	Structural Acceptance Test for Concrete Primary Reactor Containments	---	71/10
		1	72/12
1.20	Comprehensive Vibration Assessment Program for Reactor Internals During Preoperational and Initial Startup Testing	---	71/12
		1	75/06
		2	76/05
1.22	Periodic Testing of Protection System Actuation Functions (Safety Guide 22)	---	72/02
1.29	Seismic Design Classification	---	72/06
		1	73/08
		2	76/02
		3	78/09
1.32	Criteria for Safety-Related Electric Power Systems for Nuclear Power Plants	---	72/08
		1	76/03
		2	77/02
1.40	Qualification Tests of Continuous-Duty Motors Installed Inside the Containment of Water-Cooled Nuclear Power Plants	---	73/03
1.41	Preoperational Testing of Redundant On-Site Electric Power Systems to Verify Proper Load Group Assignments	---	73/03
1.52	Design, Testing, and Maintenance Criteria for Post Accident Engineered-Safety-Feature Atmosphere Cleanup System Air Filteration and Absorption Units of Light-Water-Cooled Nuclear Power Plants	---	73/06
		1	76/07
		2	78/03

Table 3.1-1 Continued.

Number	Title	Rev.	Issued Year/Month
1.55	Concrete Placement in Category 1 Structures	---	73/06
1.57	Design Limits and Loading Combination for Metal Primary Reactor Containment System Components	---	73/06
1.60	Design Response Spectra for Seismic Design of Nuclear Power Plants	---	73/10
		1	73/12
1.61	Damping Values for Seismic Design of Nuclear Power Plants	---	73/10
1.63	Electric Penetration Assemblies in Containment Structures for Light-Water-Cooled Nuclear Power Plants	---	73/10
		1	77/05
		2	78/07
1.69	Concrete Radiation Shields for Nuclear Power Plants	---	73/12
1.73	Qualification Tests of Electric Valve Operators Inside the Containment of Nuclear Power Plants	---	74/01
1.80	Preoperational Testing of Instrument Air Systems	---	74/06
1.81	Shared Emergency and Shutdown Electric Systems for Multi-Unit Nuclear Power Plants	---	74/06
		1	75/01
1.84	Code Case Acceptability - ASME Section III Design and Fabrication	---	74/06
		1	75/04
		2	75/06
		3	75/09
		4	75/11
		5	76/02
		6	76/05
		7	76/08
		8	76/11
		9	77/03
		10	77/08
		11	77/11
		12	78/03
		13	78/07
		14	78/11
1.89	Qualification of Class 1E Equipment for Nuclear Power Plants	---	74/11

Table 3.1-1 Continued

Number	Title	Rev.	Issued Year/Month
1.92	Combining Modal Responses and Spatial Components in Seismic Response Analysis	--- 1	74/12 76/02
1.97	Instrumentation for Light-Water-Cooled Nuclear Power Plants to Assess Plant Conditions During and Following an Accident	--- 1	75/12 77/08
1.100	Seismic Qualification of Electric Equipment for Nuclear Power Plants	--- 1	76/03 77/08
1.108	Periodic Testing of Diesel Generator Units as Onsite Electric Power Systems at Nuclear Power Plants	--- 1	76/08 77/08
1.116	Quality Assurance Requirements for Installation, Inspection, and Testing of Mechanical Equipment and Systems	--- 0-R	76/06 77/05
1.118	Periodic Testing of Electric Power and Protection Systems	--- 1 2	76/06 77/11 78/06
1.122	Development of Floor Design Response Spectra for Seismic Design of Floor-Supported Equipment or Components	--- 1	76/09 78/02
1.124	Service Limits and Loading Combination for Class 1 Linear-Type Component Supports	---- 1	76/11 78/01
1.125	Physical Models for Design and Operations of Hydraulic Structures and Systems for Nuclear Power Plants	--- 1	77/03 78/10
1.127	Inspection of Water-Control Structures Associated with Nuclear Power Plants	--- 1	77/04 78/03
1.128	Installation Design and Installation of Large Lead Storage Batteries for Nuclear Power Plants	--- 1	77/04 78/10
1.129	Maintenance, Testing, and Replacement of Large Lead Storage Batteries for Nuclear Power Plants	--- 1	77/04 78/02
1.130	Service Limits and Loading Combinations for Class 1 Plate-and-Shell-Type Component Supports	--- 1	77/07 78/10

Table 3.1-1 Continued.

Number	Title	Rev.	Issued Year/Month
1.131	Qualification Tests of Electric Cables, Field Splices, and Connections for Light-Water-Cooled Nuclear Power Plants (For Comment)	---	77/08
1.133	Loose-Part Detection Program for the Primary System of Light-Water-Cooled Reactors (For Comment)	---	77/09
1.137	Fuel-Oil Systems for Standby Diesel Generators (For Comment)	---	78/01
1.140	Design, Testing, and Maintenance Criteria for Normal Ventilation Exhaust System Air Filteration and Absorption Units of Light-Water-Cooled Nuclear Power Plants (For Comment)	---	78/03
1.142	Safety-Related Concrete Structures for Nuclear Power Plants (Other than Reactor Vessels and Containments) (For Comment)	---	78/04

TABLE 3.1-2 IEEE SEISMIC QUALIFICATION REQUIREMENTS FOR NUCLEAR EQUIPMENT

Number	Title
535-1979	Qualification of Class 1E Lead Storage Batteries for Nuclear Power Generating Stations
567-1980	Criteria for the Design of the Control Room Complex for a Nuclear Power Generating Station
603-1980	Trial-Use Criteria for Safety Systems for Nuclear Power Generating Stations
627-1980	Design Qualification of Safety Systems Equipment Used in Nuclear Power Generating Stations
649-1980	Qualifying Class 1E Motor Control Centers for Nuclear Power Generating Stations
650-1979	Qualification of Class 1E Static Battery Chargers and Inverters for Nuclear Power Generating Stations
C37.98-1978	Seismic Testing of Relays
ANSI N13.10-1974	Specification and Performance of On-Site Instrumentation for Continuously Monitoring Radioactivity in Effluents
317-1976	Electrical Penetration Assemblies in Containment Structures for Nuclear Power Generating Stations
323-1974	Qualifying Class 1E Equipment for Nuclear Power Generating Stations
334-1974	Type Test of Continuous Duty Class 1E Motors for Nuclear Power Generating Stations
344-1975	IEEE Recommended Practices for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations
381-1977	Criteria for Type Tests of Class 1E Modules Used in Nuclear Power Generating Stations
382-1980	Type Test of Class 1E Electric Valve Operators for Nuclear Power Generating Stations
384-1981	Criteria for Independence of Class 1E Equipment and Circuits
387-1977	Criteria for Diesel-Generator Units Applied as Standby Power Supplies for Nuclear Generating Stations

methods typically are used to demonstrate the seismic qualification of equipment: 1) test, 2) analysis, or 3) combined test and analysis. Qualification of electrical equipment is principally guided by IEEE 323-1974 and 344-1975. Additional requirements can be imposed by standards for specific types of equipment. Qualification of mechanical equipment not only has been based upon the above standards, but also on regulatory guides, ASME codes, and other applicable standards. Recently, however, drafts of regulatory guides for equipment qualification in mild and harsh environments have been circulated.

Seismic qualification of equipment requires that equipment be subjected to operating base earthquakes (OBE)and safe shutdown earthquakes (SSE), and that other significant environmental factors be included. The operating base earthquake as defined in IEEE 344-1975 is that earthquake which could reasonably be expected to affect the plant site during its operating life of the plant; it is that earthquake which produces the vibratory ground motion for which those features of a nuclear power plant necessary for continued operation without undue risks to health and safety of the public are designed to remain functional. The safe shutdown earthquake as defined in IEEE 344-1975 is that earthquake which produces the maximum vibratory ground motion for which certain structures, systems, and components are designed to remain functional. The structures, systems, and components of concern are those necessary to assure; (1) integrity of the reactor coolant pressure boundary, (2) the capability to shutdown the reactor and maintain it in a safe shutdown condition, or (3) the capability to prevent or mitigate the consequences of accidents which could result in potential offsite exposures comparable to the guideline exposure of 10 CFR Part 100, as issued on December 5, 1973.

3.2.1 Analytical Methods

Analytical qualification of a component or system is usually accomplished using one of four techniques, where application along each of the three axes simultaneously is included. These techniques are: equivalent static analysis, time history analysis, response spectrum analysis, or statistical analysis. The equivalent static analysis technique as described in IEEE 344-1975 requires no determination of the natural frequencies of the system, but the response of the equipment is assumed to be at the peak of the required response spectra at a conservative and justifiable value of damping. For frame type structures, this peak response is then multiplied by the static coefficient of 1.5. Presently, the NRC requires justification for the use of the multiplicity factor of 1.5 described in IEEE Standard 344-1975. The seismic forces on each component of the equipment are obtained by multiplying the value of the mass and the acceleration with the value obtained using the above prescribed procedure. The resultant force is then distributed over the component in a manner which is proportional to its mass distribution. These forces are then used in a static analysis of the component. The static coefficient of analysis has been extensively used in the past, however, with the availability of high speed, digital computers and reliable validated programs, this method is falling into disuse.

Two analytical methods using the time history of seismic signals are commonly used. One technique using time history of the actual earthquake event requires modal analysis of the structure. The second technique is a direct integration of the equations of motion without regard to the form of the equations. For the time history response using modal analysis, the equations of motion for the system are solved by a separation of variables technique. By the use of modal functions the formulation is reduced to an uncoupled set of ordinary differential equations in time. Responses are combined as subsequently described.

For direct time history, response calculations for each mode are carried out by applying the input earthquake using a form of the Duhamel integral. After the response for each mode has been established, it is then summed to that of other modes - a legitimate operation only when the system differential equations are linear and the overall response of the system is identified. This summation allows the response at specified locations to be determined at any specified time increment. Structural response can be obtained by direct integration of the appropriate equations of motion excited by the time history. This technique can be used for systems which include nonlinearities.

Biggs[319], Wiegel[321] and Newmark[322] describe in detail the application of the response spectrum technique for calculating the response of equipment. Briefly, the application of this technique first requires the calculation of the undamped natural frequencies and mode shapes of a mathematically modeled physical structure. Next the modal participation factors at each mode are calculated; then the maximum modal displacement is determined from the response spectrum of the earthquake evaluated at the structural resonant frequency, multiplied by the modal participation factor. The response spectrum for each mode includes damping at a value assumed to be appropriate for the respective mode. The responses of each mode are then combined using one of a variety of modal combination techniques.

R.G. 1.92 specifies the method acceptable by the NRC for combining closely spaced modes. It is generally recognized that the absolute sum of the responses provide a greatest upper bound, and for widely spaced modes the square root of the sum of the squares of individual modal responses provide a realistic assessment of the response. However, Coats[273] indicates certain conditions for which the SRSS method is inappropriate. In addition to these modal combination techniques numerous other modal combinations have been proposed. Table 3.2-1 lists some of the combination techniques[117, 331] which have been used.

3.2.2 Test Methods

Experimental qualification of nuclear plant equipment and components is guided by both IEEE 344-1975 and IEEE 323. Mechanical equipment is also qualified using similar procedures. IEEE 323 specifically recommends preconditioning the components to be qualified in a justifiable sequence. Generally, the steps in this environmental aging sequence are done in series rather than simultaneously. However, the NRC is presently requiring justification for series preconditioning using state-of-the-art information. Preconditioning attempts to place the equipment or component in a condition that would be expected to exist at its end of life. The preconditioning usually includes the following processes but not necessarily in the following order.

TABLE 3.2-1 SELECTED MODAL COMBINATION METHODS

Method 1

$$\bar{Y}_i = \sqrt{\sum_{L} (\varphi_{iL}\, q_L\, \mathrm{FACTOR}_L)^2}$$

Method 2

$$Y_{ig} = \sum_{M} \left| \varphi_{iM}\, q_M\, \mathrm{FACTOR}_M \right|$$

Method 3

$$\bar{Y}_i = \sqrt{\sum_{n} (\varphi_{in}\, q_n\, \mathrm{FACTOR}_n)^2} + Y_{ig} + Y_{ig+1} \cdots$$

Method 4

$$\bar{Y}_i = \sqrt{\sum_{n} (\varphi_{in}\, q_n\, \mathrm{FACTOR}_n)^2 + (Y_{ig})^2 + (Y_{ig+1})^2 \cdots}$$

Method 5

$$\bar{Y}_i = \left| R_L \right| + \sqrt{\sum_{L} (\varphi_{iL}\, q_L\, \mathrm{FACTOR}_L)^2 - R_L^2}$$

where R_L = the largest modal response contribution.

Method 6 *

$$\bar{Y}_i = \left[\sum_{k=1}^{L} R_k^2 + 2\sum_{\substack{j,k \\ j \neq k}} \left| R_j \; R_k \right| \right]^{1/2}$$

$$R = \varphi_i\, q\, \mathrm{FACTOR}$$

*(Method described in R.G. 1.92 (1975), and acceptable to the NRC).

Table 3.2-1 Continued

Method 7

$$\overline{Y}_i = \left[Y_{X1}^2 + Y_{X2}^2 + Y_{X3}^2 \right]^{1/2}$$

Using the individual contributions obtained in Method 6, where

L = all modal vectors selected for this analysis

M = a 'group' of modal vectors

n = all other modal vectors not designated as part of any group

ϕ_i = the modal displacement, or stress at the i^{th} d.o.f.

q = the generalized modal response

FACTOR = optional modal response factor supplied by user

Y_{ig} = the modal group sum at the i^{th} d.o.f. or stress

$\overline{Y}_i$ = the RSS response of the i^{th} d.o.f. or stress

Before tests which stress the equipment are performed, baseline inspection and operability tests must be performed. Then the equipment is exposed to elevated temperatures for a relatively short period of time. This time is often established using the Arrhenius equation, however other techniques have been employed in the past for establishing the relationship between age and thermal activity[324]. One of the more popular past techniques used is the 10°C rule. This method is not currently endorsed by the NRC. However the method of Arrhenius has received some limited discussion by the NRC and others in NUREG 0588. In addition to thermal aging, the equipment must be exposed to a radiation source, if the materials are susceptible to radiation damage. The source now recommended by NUREG 0588 is Cobalt 60 arranged to subject the equipment to the estimated total radiation field. In addition to thermal aging and radiation aging, the equipment also must be subjected to a simulated operational service life. Furthermore, if the equipment is subject to environmentally induced vibration (Safety Relief Valve, motor operation; etc.), then the equipment must be aged to account for this effect.

After the component has been subject to aging, then it must be seismically tested. Seismic qualification consists of two distinct tests. First the equipment is subjected to low level vibration tests to identify its dominant structural response characteristics and resonance frequencies. This limited modal survey is not actually a qualification requirement, but is usually included for design information purposes. Then, the equipment is subjected to a seismic test series simulating several OBE's and one SSE. During this series the equipment must be mounted so that any other significant mechanical influences are included. Also, it is operated functionally before, during, and after each event.

The type of signals used to excite the equipment to the required seismic level is quite diverse. Today, the common simulation techniques include the use of an artifically generated simulator motion, such that the test response spectrum (TRS) envelops a specified required response spectrum (RRS). Furthermore, the details of the simulation depend on whether the required motion represents a ground level or building floor level input to the equipment. Some of the typical methods used to simulate both the SSE and OBE are summarized in Table 3.3-2. In the past, the simpler methods were used to simulate in some measure the broad frequency content of ground motion. However, since 1975 the use of biaxial independent axis excitation has been recommended. Finally, after the component has been subjected to the seismic qualification routine, post accident tests and inspection are performed. For this final inspection test, disassembly of the equipment may be required.

Seismic qualification of equipment and components by testing may be accomplished by using a variety of seismic simulators. Table 3.3-3 lists examples of types of seismic simulators at various test facilities. This table shows the possibility of using one actuator to input statistically dependent motion in three directions, as well as using two and three actuators to input statistically independent motion in two or three directions simultaneously. IEEE 344-1975 discusses the use of the various types of simulators which input one or more axis of motion. This standard states that "the direction of test input motion should be in all principle axes simultaneously." However, at the present time only limited facilities in the U.S. are known to have this capability. Therefore several satisfactory alternatives are described. The standard allows single axis tests, if the tests are designed to conservatively reflect the seismic event at the equipment mounting location, or if the equipment being tested can be shown to respond independently in each of the three orthogonal axes or otherwise withstand the seismic event at its mounting location. This is the case if the coupling is zero or very low, or if other justification can be provided. If the conditions necessary for single axis testing do not apply, then multiple axes testing is specified. The recommended acceptable multi-axis testing according to IEEE Std. 344-1975 is biaxial testing with simultaneous, independent inputs in a principle horizontal and vertical axis.

Methods for synthesis of the seismic simulator drive signals required to produce the types of excitation listed in Table 3.3-2 are a very important consideration in qualification testing. The importance of proper frequency content in excitation waveforms has been stressed by Kana, et al[086]. Figure 3.2-1 shows two basic types of setups that

TABLE 3.3-2 TYPICAL METHODS OF SEISMIC SIMULATION FOR QUALIFICATION TESTS

Test Type No.	Excitation Criteria	Excitation Type	Excitation Synthesis Method	Excitation Axis
	NARROW FREQUENCY BAND TESTS (Controlled Input or Response Spectrum)			
1	Sine Sweep	Simple Harmonic	1-35 Hz Oscillator and Amplitude Controller	Uniaxial
2	Sine Dwell	Simple Harmonic	Dwell at 1/3-Octave Freq. and/or Resonant Freq. below 35 Hz	Uniaxial or Dep. Biaxial
3	Decaying Sine	Decaying Sine	Decaying Sines at Various Freq.	Uniaxial or Dep. Biaxial
4	Sine Beat	Amplitude Modulated Sine	Sine Beats at Various Frequencies; 1/3 or 1/6 octave or Resonance below 35 Hz	Uniaxial or Dep. Biaxial
5	Narrow Band Random	Tuned Narrow Band Random	Filtered Random with Tuned Center Frequency	Uniaxial Dep. or Ind. Biaxial
		BROAD FREQUENCY BAND TESTS (Response Spectrum)		
6	Wide Band Random	Multiple Random Freq. Bands	Analog summation of Ind. Random Freq. Bands	Dep. or Ind. Biaxial
7	Complex Analog	Multiple Freq. Bands	Analog Summarion of Ind. Sine, Sine Decay, Sine Beat, or Random	Dep. or Ind. Biaxial
8	Complex Digital	Multiple Freq. Bands	Digital Synthesis of Complex Wide Band Random Signal	Dep. or Ind. Biaxial

allow adjustment of energy content in successive frequency bands. Digital techniques allow the narrowest frequency resolution and speed of process completion. Figure 3.2-2 shows a diagram of such a setup where the process is controlled in 1/6-octave frequency bands on each axis of a biaxial table. Details of this method have been published by Unruh[269].

TABLE 3.3-3 TYPES OF SEISMIC SIMULATORS AT VARIOUS U.S. TEST FACILITIES

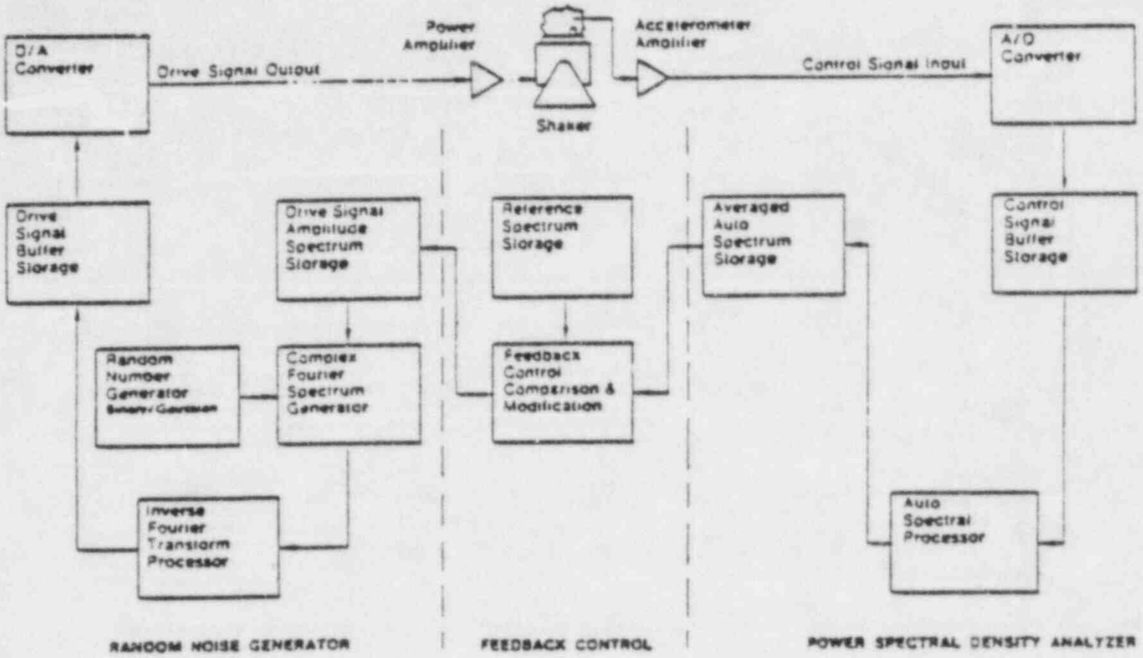
Company	Type of Test Facility
ACTON Environmental Testing	DB
ANCO Engineers	A, IB, IT
Approved Engineer Test Labs/NTS	DB, IB
Structural Dynamics Research Corporation	DB, IB, IT
Wyle	IB, DB, IT
University of California, Berkley	IB
Franklin Research Institute	DB
Westinghouse	DB
Combustion Engineering	DB
Bailey Meter Company	DB
Southwest Research Institute	IB
General Electric Company (San Jose)	IB
Dayton T. Brown	A

DB - Dependent Biaxial

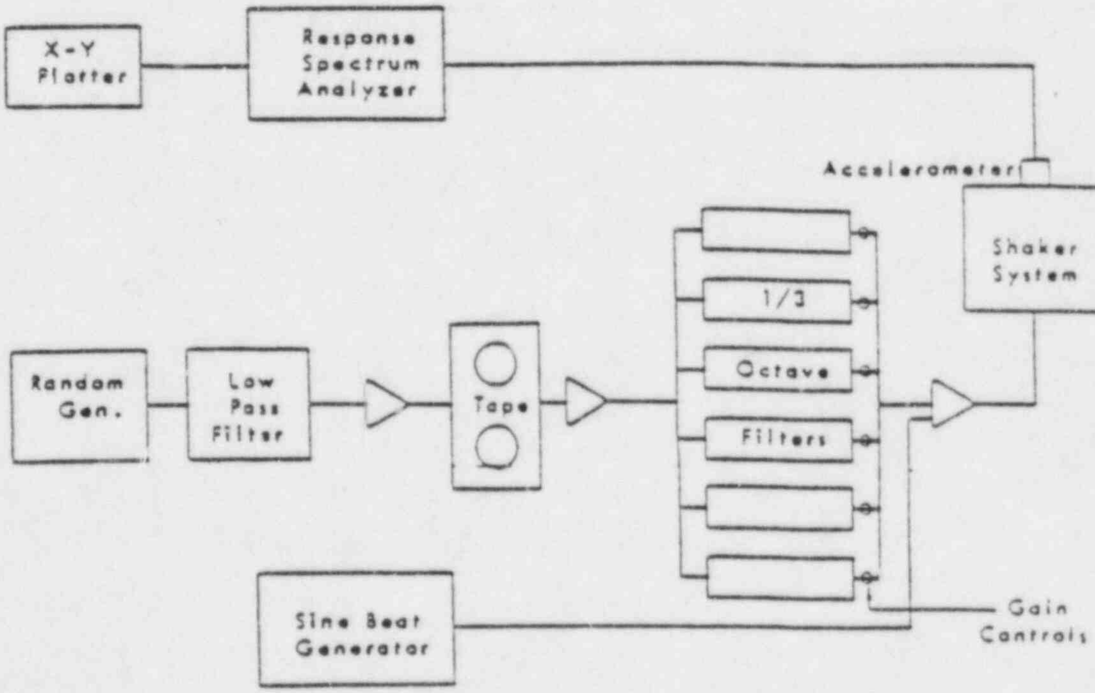
IB - Independent Biaxial

IT - Independent Triaxial

A - Single Axis



DIGITAL TYPE SYNTHESIS



ANALOG TYPE SYNTHESIS

Figure 3.2-1 Schematics of Typical Waveform Synthesis Techniques
(From Ref. 087)

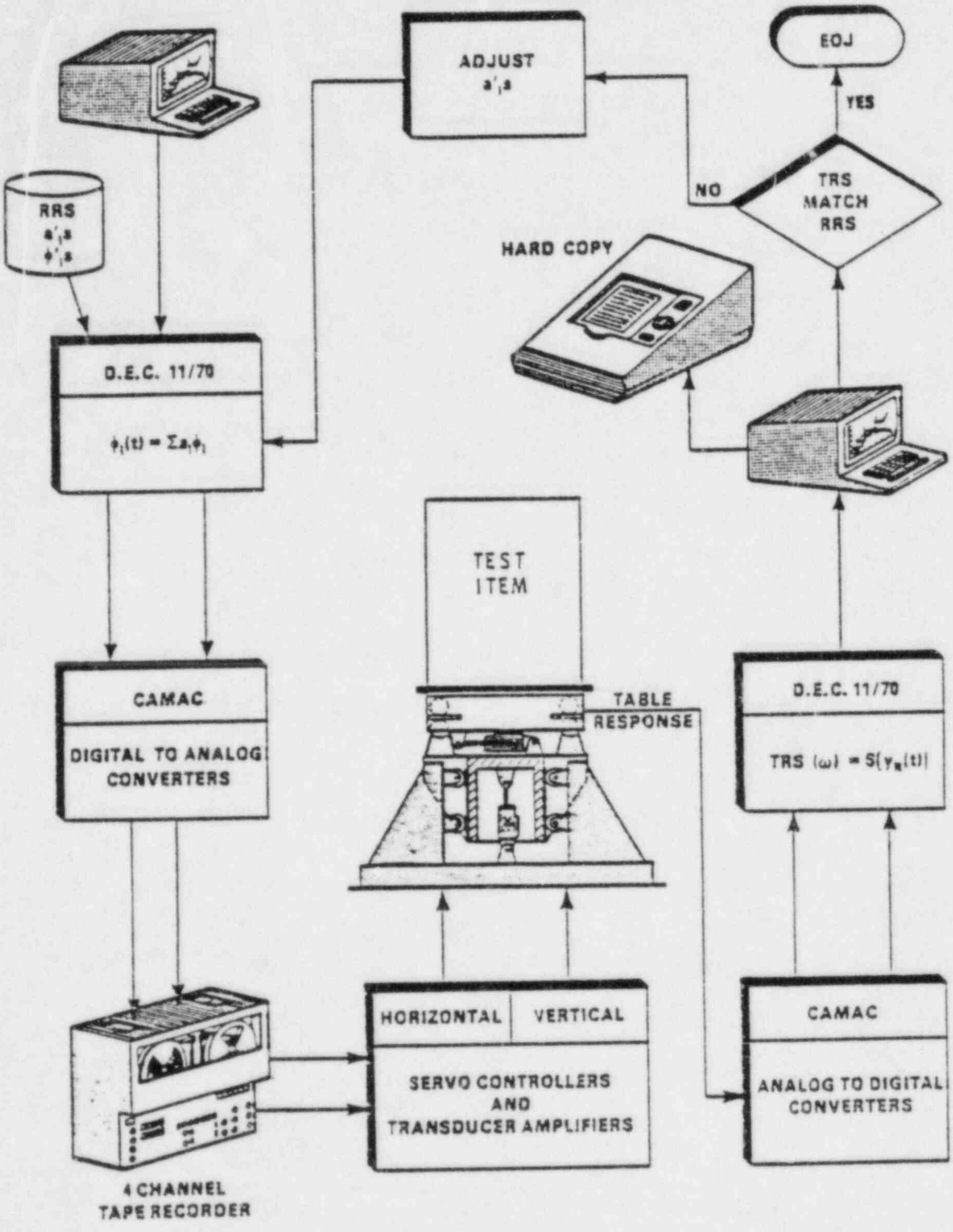


Figure 3.2-2 Seismic Simulator Digital Control Process
(From Ref. 269)

4.0 EQUIPMENT QUALIFICATION SUMMARIES

Items which are assembled to form an operating nuclear power plant come in all shapes and sizes. Electronic and electrical items range, in size, from pieces of wire to assemblies of relays, instruments, etc., and, mechanical items range in size, from small machine screws to vessels weighing more than 100 tons. This diverse array of equipment has been classified into 11 generic groups, as was indicated in Table 2.3-1, and for the purpose of this review, is defined to include all the mechanical and electrical components which must be qualified in any given nuclear plant. These 11 generic groups, as shown in Table 4.0-1, have been further subdivided into subgroups. The number of these subgroups depends upon the particular generic group. For each generic subgroup Table 4.0-1 specifies the typical location, typical function, the operational state, size/shape, method(s) known to have been used to seismically qualify the type of equipment, and a cross-reference number to original entries given in Table 2-1 of Ref. [087] (note that in some cases no exact cross-reference is possible), which is included herein in Section 9.0. The operational state refers to whether items contained within the generic device must move in order for the equipment to perform its intended function. An example of an active device is switchgear (Subgroup 4.3). This device transfers a load from one location to another by rearranging internal contacts; hence, switchgear is an active device. An example of a passive device is a thin walled storage tank (Subgroup 4.10). No motion of any portion of this device is required for it to contain its internal fluid. The meaning of the remaining four parameters is evident.

Table 4.0-1 is intended as a quick summary for qualification information, while the following sections describe in more detail the function of each equipment subgroup and the method known to have been used to seismically test the equiment. The detailed qualification information and data presented in the following sections is based upon the information sources identified in Section 2.2. Often the results of seismic qualification programs for equipment are retained as proprietary by the equipment manufacturers.

TABLE 4.0-1 EQUIPMENT AND COMPONENT CATEGORIZATION

Generic Group	Generic Subgroup	Typical Location	Typical Function	Operational State	Size/Shape	Method of Qualification
Electric Equipment Mounts	Panels (4.1.1) [23]*	Near the location where attached equipment is used.	Support isolated components.	Passive	Open or closed small structures containing relatively few components.	Qualified by test.
	Racks (4.1.2) [23]	Throughout plant, often used in clusters in protected areas.	Group related components together in an organized fashion to form a complex system.	Passive	Relatively large open frame type structures often w/ many components	Qualified by test.
	Cabinets (4.1.3) [23]	Throughout plant, often used in clusters in protected areas.	Group related components together in an organized fashion to form a complex system.	Passive	Relatively large closed box type structures formed from structural steel & plate containing many components.	Qualified by test.
Electrical Instrument Devices	Transducers including integral signal conditioners (4.2.1) [23]	Throughout plant.	Monitor specific process variables.	Active	Relatively small devices often containing complex electrical and mechanical devices.	Qualified by test.
	Computer Systems [23] (4.2.2)	Near control room in a protected area.	Store, analyze and act on information received from instrumentation.	Active	Depends on age of computer system, varies from a few cabinets of equipment to a small room full of equipment.	Qualified by test.
	Communication Systems [23] (4.2.3)	Individual stations throughout plant but master console in control room.	Visual surveillance of specific plant areas and verbal communications between personnel.	Active		

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[*] Numbers in brackets refer to Item numbers in Table 2-1 of Ref. 087 (See Section 9.0).

TABLE 4.0-1 EQUIPMENT AND COMPONENT CATEGORIZATION

Generic Group	Generic Subgroup	Typical Location	Typical Function	Operational State	Size/Shape	Method of Qualification
Electrical Power Devices	Switchgear (4.3.1) [22]	Auxiliary buildings.	Transfer electrical loads	Active	Individually components are relatively small but clustered in large groups.	Qualified by test.
	Transformers (4.3.2) [23]	Auxiliary buildings and in most electronic systems.	Provides appropriate voltages and emergency safety function systems.	Passive	Compact devices which are heavy relative of their size.	Very large units are qualified by analysis. Smaller units are qualified by test.
	Inverters (4.3.3) [23]	Auxiliary buildings.	AC-DC power conversion for emergency safety function systems.	Passive	Moderate size systems contained on racks or in cabinets.	Qualified by test.
	Emergency Diesel Generators (4.3.4) [20]	In an auxiliary building often designated the Diesel Generator Building.	Provides emergency electrical energy to safety related systems.	Active	A compact, heavy assemblage of mechanical & electrical components whose combined weight is in excess of 70 ton	Qualified by analysis and test.
	DC Power Units, e.g., batteries, etc. (4.3.5 [21]	In a protected area of an auxiliary building near the control room.	Provides emergency short term electrical energy to safety related systems	Passive	Large groups of connected lead acid (usually) batteries supported by a rack forming a heavy compact system.	Individual units are qualified by tests. Complete battery systems are then qualified by analysis.
Valves	Large Power Operated Valves - air or electric (4.4.1) [15,17]	Throughout plant	Isolation and control of coolant flow.	Active	Body of valve designed to be compatible with attached pipe. Actuator usually attached by a relatively flexible structure.	Very large valves are qualified by analysis. Limited tests are performed to verify predicted dynamic characteristics.

TABLE 4.0-1 EQUIPMENT AND COMPONENT CATEGORIZATION

Generic Group	Generic Subgroup	Typical Location	Typical Function	Operational State	Size/Shape	Method of Qualification
Valves	Relief Valves (4.4.2) [16]	Throughout plant.	Automatically responds to release system pressure at a preselected level.	Active	Relatively long slender structures providing pressure sealing by metal-to-metal seats.	Very large relief valves are qualified by analysis Smaller relief valves are qualified by tests.
	Check Valves (4.4.3) [16]	Throughout plant.	Prevents backflow in systems.	Active	Relatively small in line devices using a ball/spring or flapper mechanism to prevent backflow.	Qualified by analysis.
	Instrumentation Valves air solenoid, electromechanical (4.4.4) [17,18]	Throughout plant.	Control isolation and injection in instrumentation systems.	Active	Small devices containing delicate internal mechanisms and often electrical devices.	Qualified by test and analysis.
Piping	Large pipes (4.5.1) [5]	Throughout plant.	Transport of large quantities of fluid.	Passive	Thick walled pipes with numerous supports. Often slender structure using strength of materials definition.	Qualification is exclusively analysis. However tests have been reported from decommissioned nuclear plants and one operating nuclear plant on resonant frequencies.
	Small pipes (4.5.2) [6]	Throughout plant.	Transport of fluid necessary.	Passive	Long slender structures with heavy walls.	Qualification by analysis
	Buried pipes (4.5.3) [11]	Underground connecting remotely located auxiliary buildings		Passive	Pipes buried in ground.	Qualification exclusively by analysis.

TABLE 4.0-1 EQUIPMENT AND COMPONENT CATEGORIZATION

Generic Group	Generic Subgroup	Typical Location	Typical Function	Operational State	Size/Shape	Method of Qualification
Pumps	Main Coolant Pumps [12,13] (4.6.1)	Containment building in the lower levels.	Circulation of primary coolant in the reactor system.	Active	Very large structures which include a powerful electric motor.	Qualification exclusively by analysis.
	Medium to Large Pumps and Compressors [13] (4.6.2)	Throughout plant.	Coolant pumos and environmental control for selected equipment.	Active	Size depends on application. Pumps can be mounted vertical, horizontal or submerged.	Qualification for larger pumps by analysis but as size decreases qualification is by testing.
	Safety Related Pumps [12,13,14] (4.6.3)	Throughout plant.	Special pumps for coolant, lubricant and transfer of other critical fluid.	Active	Size depends on application. Pumps can be mounted vertical, horizontal or submerged.	Type of qualification depends on size.
Heat Removal Systems	Heat Exchangers (4.7.1)	Auxiliary buildings.	Transfer heat from critical components.	Passive	Generally large bulky devices. Often heat exchange is surrounded by heavy walled vessel.	Qualification by analysis.
	Steam Generators (4.7.2)	Containment building in a structurally protected area.	Remove heat from primary coolant.	Passive	Very large structures. Can weigh in excess of 50 ton.	Qualification exclusively by analysis. However, tests have been reported.
	Emergency Pump Drive Systems (4.7.3)	In an auxiliary building often designated as the Diesel Generator Build-	Provide emergency cooling of the reactor during an accident.	Active	A compact, heavy assemblage of mostly mechanical components whose combined weight is in excess of 30 tons.	Generally qualified by combined analysis and tests. Tests are performed to identify structural dynamics properties which are used to confirm analytical results. One system is known to have been seismically qualified by testing.

TABLE 4.0-1 EQUIPMENT AND COMPONENT CATEGORIZATION

Generic Group	Generic Subgroup	Typical Location	Typical Function	Operational State	Size/Shape	Method of Qualification
	Large Cooling Fans, Motors, Generators and Compressors [19] (4.7.4)	Throughout plant.	Provide electrical energy to select equipment and ventilation systems.	Active	Compact devices and usually heavy for their size.	Large units are qualified by analysis. Smaller units are qualified by test.
Air Conditioning Systems	Air Ducting (4.8.1) [25]	In containment and buildings in the immediate vicinity.	Conduct conditioned air to designated areas for cooling and biological needs.	Passive	Large bulky structures formed from structural steel, plate and sheet. Usually lightweight for relative size.	The ducts are qualified by analysis which use lump mass finite elements and beams. Limited tests have been performed.
	Air Conditioning and Filtering (4.8.2)	In containment and buildings in the immediate vicinity.	Provide cooled air and biologically safe air.	Active	Large bulky structures usually lightweight for relative size.	Qualification is by analysis.
System Support Facilities	Cable Trays (4.9.1) [24]	Throughout plant.	Support individual and bundle of wires used to control and power reactor systems.	Passive	Long slender lightweight beam type structures supported by open frame work.	Generally qualified by analysis. However, tests have been performed showing comparison with analysis.
	Fuel Storage Racks (4.9.2)	Spent fuel storage area or other specifically designated secure areas.	Support used or new fuel assemblies in the proper environment.	Passive	Space frame type structures fabricated from structural shapes.	Generally qualified by analysis. Analysis uses codes employing beam elements.
	Reactor Containment and Facilities Building (4.9.3)	Surrounding reactor and other systems important to safety.	Provides a secure structure to house the reactor, support safety systems and mitigate the effects of a nuclear accident.	Passive	Generally large, massive concrete and steel structures.	Qualification is exclusively analysis. Tests have been reported on decommissioned nuclear plants and one operating plant which is useful to identify resonant frequencies.

TABLE 4.0-1 EQUIPMENT AND COMPONENT CATEGORIZATION

Generic Group	Generic Subgroup	Typical Location	Typical Function	Operational State	Size/Shape	Method of Qualification
	Internal Reactor Structures (4.9.4) [2]	Inside containment in reactor vessel.	Support nuclear cone, contain the reactor coolant and protect the core.	Passive	Large stainless steel precision machined components Complete set of reactor internals can weigh in excess of 100 tons.	Qualification is exclusively analysis. However preoperational tests are performed on prototype plants which can be used to substantiate predicted resonant frequencies.
Vessels	Large Vertical Vessels [7,8] (4.10.1)	Throughout plant.	Used to contain fluid necessary for reactor operation.	Passive	Large heavy structures of various shapes.	Qualified by analysis.
	Large Horizontal Vessles (4.10.2) [9,10]	Throughout plant.	Used to contain fluid necessary for reactor operation.	Passive	Large heavy structures of various shapes.	Qualified by analysis.
	Reactor Coolant System [1] (4.10.3)	Inside containment	Contains the fluid used to cool the core and support other internal reactor structures.	Passive	Very thick vessels designed to withstand all postulated accidents and mitigate effects of a nuclear accident.	Qualified by analysis.
Miscellaneous Components	Snubbers (4.11.1)	Throughout plant.		Active	Size and weight varies depending on pipe being restrained.	Generally qualified by tests.

TABLE 4.0-1 EQUIPMENT AND COMPONENT CATEGORIZATION

Generic Group	Generic Subgroup	Typical Location	Typical Function	Operational State	Size/Shape	Method of Qualification
	Fuel Rod Assemblies [3] (4.11.2)	Inside reactor vessel surrounded by internal reactor structures.	Contains pellets of enriched Uranium used to fuel the reactor.	Passive	Bundles of cylindrical rods properly spaced by a "egg crate" type structure. A single commercial PWR fuel assy. weighs in excess of 1500 lb.	Generally qualified by combining analysis and tests. Tests are performed to determine structural properties of spacer grids. These results are combined using lumped mass analysis to predict seismic response of the fuel assembly.
	Control Rod Drive Mechanisms (4.11.3) [4]	Attached to reactor vessel.	Mechanisms used to control the rate of nuclear reaction.	Active	Very long slender structure used to insert rods or plates to control nuclear reaction rate.	Majority are qualified by analysis. However, limited qualification by tests has been reported.

Knowledge of the detailed excitation and response characteristics, e.g., temperature, pressure, response spectrum, etc., are necessary for an equipment user to judge the adequacy of the qualification program. Qualification statements by manufacturers attesting only that equipment has been qualified in accordance with a particular IEEE standard are unacceptable. IEEE standards are not specific "cookbook" formulas but, procedural guides. Blind adherence to a standard does not insure component qualification. Each qualification step requires justification and comparison to plant and site specific parameters.

4.1 Electrical Equipment Mounts

GENERIC COMPONENT GROUP: Electric Equipment Mounts

4.1.1 GENERIC COMPONENT SUBGROUP: Panels

DESCRIPTION: A panel is a small open frame or enclosure designed for grouping various types of electric or electronic devices including buses, relays, automatic controllers, meters or signal conditioning electronics. These panels are usually formed from sheet metal. Often they are surrounded by some type of enclosure with a securely locking door which prevents tampering or unauthorized maintenance. Depending upon the location, the components may be waterproof.

WEIGHT: Panels and their contents commonly weigh from a few pounds to approximately 200 pounds. However, the exact weight can vary significantly depending on the type of material and the material gage used for their construction and other embellishments.

TYPICAL MOUNTING: Panels can be attached by fasteners or welds to embedded beams, fastened or welded to equipment skids, floor mounted and clamped, bolted or welded to various types of structural supports. They are often attached to the wall of a room in the plant.

SEISMIC QUALIFICATION METHOD: Panels are qualified by either analysis or testing. The type of qualification depends on the complexity of the panel. For panels with simple geometric shapes qualification can be obtained using equations derived from strength of materials; more complex shapes are analyzed using finite element computer codes. Even if qualification by analysis is possible, panels are often qualified by testing. The dynamic input is usually a response spectrum.

AGING: Panels, excluding mounted components, are fabricated from metallic type materials hence radiation, thermal or post-accident aging is not required. No reference was found which suggest panels were aged to include the effects of the normal operational vibration environment. However, from experience, the authors have observed panel installations with severe environmental vibration. More recently, consideration is being given to fatigue effects from repeated hydrodynamic vibration events.

FAILURE MODES
AND ACCEPTANCE
CRITERIA: Panel failures usually include cracks, broken welds, torn mounting holes, loose fasteners or general structural degradation. Presence of such failures is acceptable providing that the item remains functional.

REFERENCES: 47*, 57, 87, 126

GENERIC COMPONENT GROUP: Electric Equipment Mounts

4.1.2 GENERIC COMPONENT SUBGROUP: Racks

DESCRIPTION: A rack is an open frame designed for mounting and supporting electrical equipment. Often racks have a series of predrilled holes to facilitate mounting or they may have rails which use T-bolts to hold the equipment in its proper place. An example of a rack is shown in Figure 4.1-1. This vertical rack was fabricated from standard structural steel shapes. Members of the rack were welded together and stategically braced for increased strength. The rack shown in Figure 4.1-1 has horizontal U-channels with rolled edges, which are used to support the required electrical or electronic equipment. The equipment is held in place by T-bolts whose heads are captured by the rolled edges of the U-channels. Often individual racks are affixed together to form a long row.

The equipment mounted on racks is extremely varied. It is usually arranged with the heavy weight items near the mounting base and the

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*Denotes most significant references.

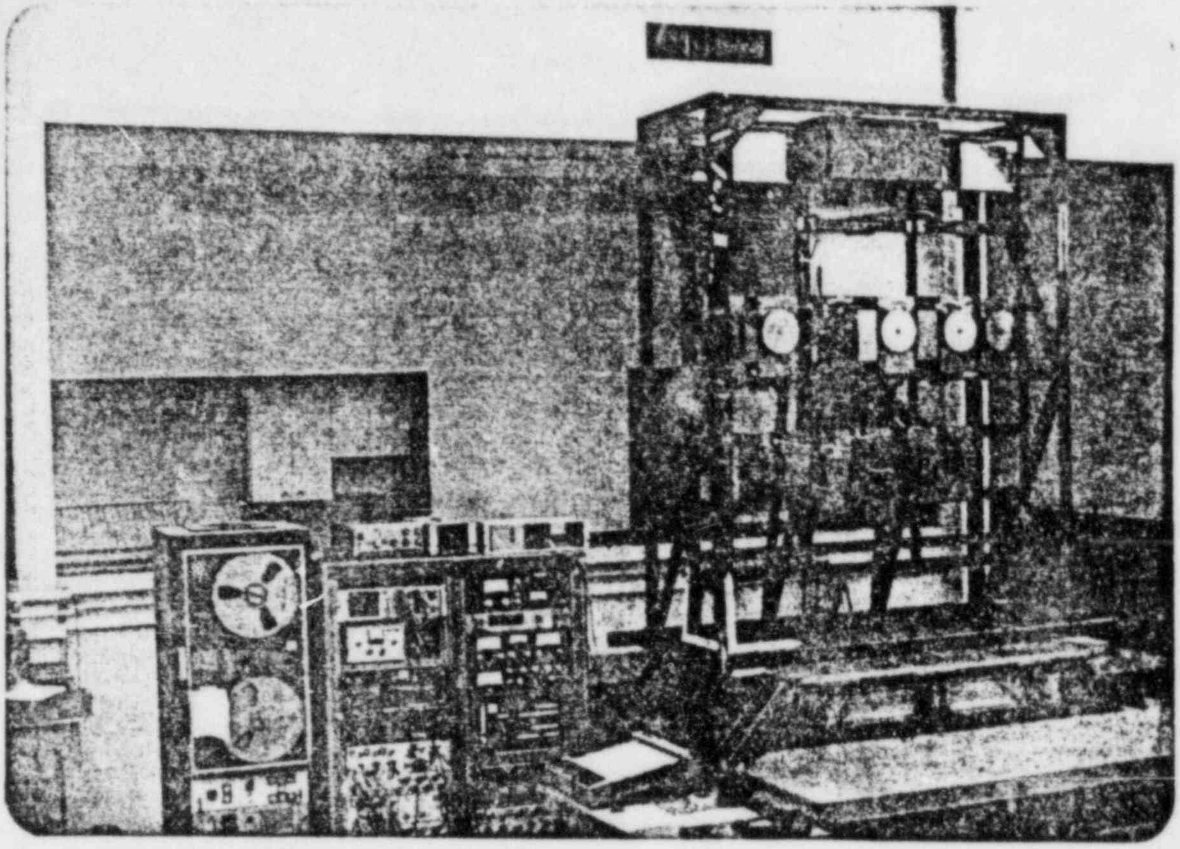

Figure 4.1-1 Typical Rack

lighter weight items near the top, although this is not always the case. Furthermore, the aggregate center of gravity may be well off the centerline of the rack itself. Lead acid batteries, used as a short-term electrical energy supply for emergency safety systems, are often mounted on racks. Mechanical components, e.g., filters, pipes, and valves, used in air sampling systems are likewise mounted on racks.

WEIGHT: Racks and their contents commonly weigh from 500-2000 pounds. However, the diversity of applications for racks prevents specifying exact upper or lower limits on either their weight or inertial properties important in seismic qualification. These must be ascertained for each individual case.

TYPICAL MOUNTING: Racks are usually free standing structures welded at the base to embedded beams or securely fastened by bolts embedded in the concrete floor. The bolts can be either located in the concrete during construction of the supporting floor or foundation, or, special fasteners can be installed during installation of the racks.

SEISMIC QUALIFICATION METHODS: Usually rack frames are qualified by generic type tests. Seismic qualification of racks includes the dynamic properties of the component mounted on the rack. The dynamic properties of the components may be 1) simulated by mounting dummy weights whose mass and size approximate the component being simulated as was done in Figure 4.1-1, or 2) the actual components as actually mounted on the rack. For further design use of the dynamic data that can be obtained during qualification, acceleration, velocity or displacement measurements are often made at selected locations as a function of input (i.e., transfer functions).

Since the release of IEEE 344-1975, seismic qualification tests for racks have included the use of simultaneous biaxial (horizontal and vertical) excitation. However, the input may or may not be statistically independent. Dependent multi-axis inputs are developed by rotating either the rack or the exciter to produce motion in multiple directions.

Seismic qualification in the 60's and very early 70's used either sine dwell or swept sine testing. Since the release of IEEE 344-1975, seismic qualification has primarily been based on the specification of a response spectrum, with sine beat and shaped random signals used to synthesize the drive signals which produce the desired excitation.

In situ tests in the late 60's and early 70's were performed to obtain the modal response characteristics of racks. These tests were primarily limited to lower modes by the excitation methods used.

Once generic rack designs have been qualified, similar designs are often qualified by analysis. The analysis is sufficiently quantitative to justify the conclusion that the similar design will withstand the same or similar environment. Often the analysis has included very simple mathematical relations for seismic qualification. More recent work has tended toward more elaborate finite element models.

AGING: Racks, excluding the mounted components, are usually fabricated from structural shapes of metallic materials. Hence, radiation or thermal aging has not been considered. No reference was found which suggests racks were aged to include the effects of normal operational vibration environment. Nevertheless, from experience, the authors have observed rack installations near large machinery. More recently, the effects of this environment are being considered.

FAILURE MODES
AND ACCEPTANCE
CRITERIA: Rack failures usually include cracks, broken welds, torn mounting holes, loose fasteners or general structural degradation. Presence of such failures is acceptable providing that the item remains functional.

REFERENCES: 4, 8, 28, 57, 63, 74, 87, 126, 131, 243*, 244*, 293

GENERIC COMPONENT GROUP: Electrical Equipment

4.1.3 GENERIC COMPONENT SUBGROUP: Cabinets

DESCRIPTION: A cabinet is an enclosed structure with swinging door(s) designed for mounting, supporting and enclosing electrical equipment. Those designed to withstand seismic disturbance have sturdy construction, including frame works using structural steel shapes to form major structural elements. These steel shapes can be on either the interior or exterior of the cabinet. The exterior skin of the cabinet is bent or welded heavy gage plate. Holes are often cut into cabinets to facilitate mounting display and controlling devices e.g., lights, switches and meters.

Figure 4.1-2 shows a typical cabinet. This figure shows that the center of the hinged cabinet door is reinforced with a wide hat channel, and the edges of the door are reinforced with formed metal. The interior of the cabinet contains a series of terminal strips fed from heavy incoming electrical cables. Input or output cables or bus bars can provide significant structural reinforcement. For cables the effect is increased by tightly bundling the wires to form a very stiff structure. Often individual cabinets are affixed together to form long rows. These rows are separated by an aisle which is usually of sufficient width to open the cabinet doors. The cabinets are located in secure areas.

For convenience, the equipment mounted in the cabinets is usually arranged according to functional requirements. The heavy components are often mounted near the base of the cabinets, and, the lighter components are mounted in the upper levels of the cabinet, although this is not always the case.

The equipment mounted in cabinets is usually quite diverse. The mounted equipment can vary from small electronic components, drawers of complex electromechanical devices to large mechanical components. Cabinets contain intricate wiring bundles connecting the various components. These bundles must survive the environmental qualification programs of the cabinet.

WEIGHT: Cabinets often weigh over 1000 pounds. However, the diversity of applications for cabinets prevents specifying either an upper or lower limit on either their weight or inertial properties important in seismic qualification.

TYPICAL MOUNTING: Cabinets are usually free standing structures welded at the base to embedded beams or affixed by bolts embedded in the concrete floor. The bolts can either be located in the concrete during construction of the supporting floor or foundation; or, special fasteners can be installed during the final installation of the cabinets. Several cabinets may be bolted together in lateral series.

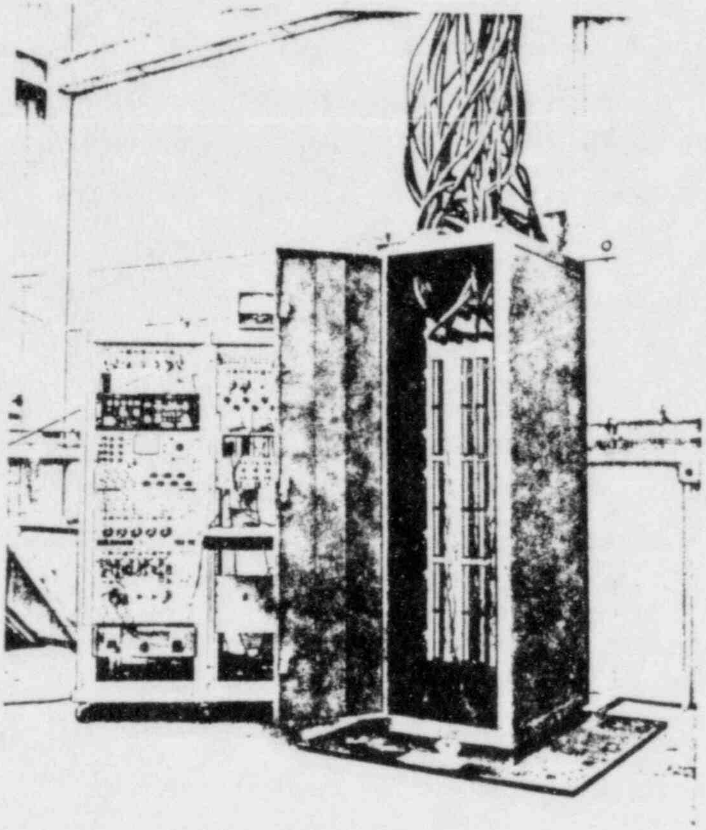

Figure 4.1-2 Cabinet

SEISMIC
QUALIFICATION
METHOD: Usually cabinets are qualified by generic tests. The qualification techniques are identical to those discussed for racks with one significant difference. Cabinets contain complex wiring arrangements for many instruments. This additional complication often limits the applicability of generic tests for cabinet seismic qualification.

Attempts have been made to qualify cabinets by analysis but they have generally been unsuccessful. The analytical cabinet qualification programs, known to the authors, used finite element computer programs. Also, analytical cabinet qualification programs have not found favor with the NRC review groups. Once a generic cabinet design has been qualified, similar designs are qualified by analysis. The analysis is sufficient to justify the conclusion that the similar design will withstand the same or similar environment. The analyses for accomplishing qualification by similarity are often more complicated than for racks or frames. However, the analyses are extrapolations rather than predictions based upon experimentally justified models. Series mounted cabinets are usually qualified by analysis.

It is not unusual for cabinets to experience rattling and banging of loosely fitting doors and appendages when excited by seizure excitation. This behavior generates nonlinear energy at frequencies which are well beyond the seismic input range. Instrumentation located in such cabinets is properly tested when included in the assembly qualification. However, if the cabinet is tested with dummy instrumentation devices with the intention of subsequent test of the actual devices based on measured responses on the cabinet, great care must be exercised to assure that the higher frequency energy is included in the subsequent device tests.

AGING: Cabinets, excluding the mounted components, are usually fabricated from structural shapes of metallic materials. Hence, radiation or thermal aging has not been considered. No reference was found which suggests cabinets were aged to include the effects of normal operational vibration environment. However, the contents of the cabinet, instrumentation and wiring are very much susceptible to aging, and will be covered under a separate topic.

FAILURE MODES
AND ACCEPTANCE
CRITERIA: Cabinet failures usually include cracks, broken welds, torn mounting holes, loosening of fasteners or general structural degradation. Presence of such failures is acceptable providing that the item remains functional.

REFERENCES: 15, 52, 54, 57, 60*, 61, 64, 68, 69, 77, 80, 86*, 87*, 119, 123*, 125, 126, 127, 131, 150*, 157, 225, 231, 276, 294, 320, 332, 334, 335*

4.2 Electrical Instruments and Devices

GENERIC COMPONENT GROUP: Electrical Instruments and Devices

4.2.1 GENERIC COMPONENT SUBGROUP: Transducers Including Integral Signal Conditioners

DESCRIPTION: A transducer is a device which is used to monitor some operational parameter by measuring the energy of the parameter directly, or by changing it to some more convenient form. The energy transmitted by these systems may be of any form, e.g., electrical, mechanical, thermal or acoustical, and it may be of the same form or different forms in the various input and output systems. Nuclear power plants employ four fundamental types of transducers: pressure, temperature, radiation, and motion.

Transducers used in nuclear power plants typically provide inputs for controlling and monitoring the plant operation. These devices respond to a physical parameter and convert this parameter to an electrical impulse. Usually this process is modified by signal conditioning circuits and amplifiers for user convenience, e.g., linearizing circuits and cube root extractors. Transducers including their signal conditioning networks are designed to operate in specific environments. Exceeding recommended operating environments often results in erratic and/or inaccurate response.

WEIGHT: Transducers are commonly lightweight small items. Their light weight is a direct result of the need to insure that the sensing element of the transducer does not interfere with the process being measured.

TYPICAL
MOUNTING: The method of mounting a transducer in a system to sense a given physical parameter requires care. However, generic mounting descriptions can be described for each class of transducers.

Pressure transducers (transmitters) are remotely mounted from the location where the pressure measurement is made. The pressure transducer is connected to the penetration by an "instrument line". The instrument lines are chosen based upon the required response time of the instrument. The actual transducer is usually mounted by bolts to a panel or on a bracket affixed to a wall or structural member.

Temperature transducers are mounted to penetrate the environment being sensed. A common type of temperature transducr is a thermowell. This is a thermocouple contained in a partially threaded tube. The tube is screwed into a properly threaded hole. These devices are often mounted in pipes.

Radiation detectors are used to sense radiation in three major locations in a nuclear reactor facility. Detectors are located: 1) in the core, 2) outside the reactor vessel and 3) to monitor environmental radiation. The instruments sensing core radiation are mounted in specially designed fixtures and, the instruments sensing environmental radiation are mounted in specially designed chambers.

Motion detectors are mounted directly to the devices whose motion is being sensed. For example, limit switches are mounted for activation by a moving device, accelerometers and/or displacement sensor are mounted on the moving structure whose motion is being sensed. Usually these devices are attached by a threaded fastener.

SEISMIC
QUALIFICATION
METHOD: Transducers and their associated signal conditioning electronics are qualified by generic type tests. The components are mounted on stiff brackets or bookends affixed to the seismic simulator.

The form of the required motion is usually a specified response spectrum or local inservice mounting simulation. The input for such tests is usually measured during tests of the mounting structure, such as a panel, rack or cabinet. The required response spectrum is the usual form for tests specified today and are achieved using sine beat or shaped random input. However, early seismic qualification tests, until approximately 1975, achieved the required input using sine dwell, swept sine, or sine beat tests. In spite of the use of such methods, there still appears to have been no effort made to determine frequency dependence of malfunction on these devices.

Today, during the seismic excitation of the instruments, performance characteristics are evaluated according to IEEE 344-1975. Generally the earlier reported qualification programs for instrumentation did not discuss in detail the monitored performance parameters. However, based on experience, the authors are aware of extensive efforts which are necessary to insure adequate performance.

Performance monitoring techniques have become progressively more sophisticated since 1970. Initial monitoring was basic confirmation of operability, but current monitoring involves operation at extreme conditions during qualification.

AGING: Current qualification procedures include a careful series of tests applied to the device to achieve the state expected to exist at the end of its life. Component aging is governed by IEEE 323-1974, the NUREG 0588 and the NRC IE Bulletin No. 79-01B. These documents were clarified by the NRC in July, 1981.

The published information reviewed on electrical instruments and devices did not contain explicit descriptions describing how the aging mechanisms of operation and environmental vibration damage were simulated. However, the authors have witnessed tests which simulate the aging mechanism of operation. Until recently, tests incorporating environmental vibration damage have not been considered, although these effects are now being reviewed carefully.

FAILURE MODES
AND ACCEPTANCE
CRITERIA: Failure criteria for electrical instruments and devices are usually based upon minimum operational requirements. These requirements can include limits defining, linearity, output, and voltage spiking. Typical failures include relay chattering, inadvertent relay opening or closing, or loss of function due to vibration of internal mechanisms. In addition to the operational properties, mechanical failure criteria are imposed which prohibit cracks, broken

welds, torn mounting holes, loosening of fasteners and general structural degradation. Acceptance of above malfunctions depends on the consequences of the result on safety.

REFERENCES: 81, 83, 84, 118, 337*

GENERIC COMPONENT GROUP: Electrical Instruments and Devices

4.2.2 GENERIC COMPONENT SUBGROUP: Computer Systems

DESCRIPTION: A computer system is a self contained machine for performing programmed actions based upon inputs, and displaying the results in some useful form. The computer system incorporates memory devices, input devices, control processor units and output devices (hard copy or cathode ray tube). The degree of sophistication of the computer system used in nuclear plants depends on the utility, designer and major control system supplier. Older computer systems require more space than newer systems which use integrated circuits. Although in older installations computers are not considered category 1, current trends are toward category 1 use in newer installations.

Various types of computer systems are used in a nuclear plant. Small computer systems are dedicated to performing one type of task, eg., data acquisition during a transient. Larger computer systems can perform system control functions using numerous inputs. Ultimate system control resides with the operator. However, computers provide information useful for guiding an operator.

WEIGHT: The total weight of the computer system depends on its age. New systems are relatively light while older systems can be heavy. The composite assembly may resemble a completely assembled electrical cabinet.

TYPICAL
MOUNTING: The various components whether electrical or mechanical are mounted in racks or cabinets. The central portion of the computer system is usually located in secure areas with environmental control. Auxiliary input or output devices can be remotely located for user convenience. Critical devices are carefully mounted; non-critical devices are conveniently mounted.

SEISMIC
QUALIFICATION
METHOD: Uncertain, but believed to be similar to racks and cabinets with devices installed.

AGING: Uncertain, but believed to be similar to racks and cabinets with devices installed.

FAILURE MODES
AND ACCEPTANCE
CRITERIA: Uncertain, but believed to be similar to racks and cabinets with devices installed. Furthermore, some dispacs and other devices are particularly sensitive to vibration, and failure modes resulting from power interruptions can occur in very short time intervals.

REFERENCES: 306

GENERIC COMPONENT GROUP: Communication Systems

4.2.3 GENERIC COMPONENT SUBGROUP: Communication Systems

DESCRIPTION: Nuclear plants employ two major types of communication systems - video and audio. Video systems are used for observing activities at multiple remote sites from one central location. Audio systems are used for discussing activities between one or more remote locations. Video systems are closed circuit television (CCTV) distributed throughout the nuclear plant. Cameras are installed for monitoring remote areas such as the fuel storage area, reactor building and perimeter barriers. Monitors and camera controllers are located to provide the required information to the responsible parties. Audio systems, (telephone, public address and warning systems) are distributed throughout the nuclear plant. These systems are used for interpersonal communications and warnings.

SEISMIC
QUALIFICATION: Uncertain, but believed to be similar to transducers.

AGING: Uncertain, but believed to be similar to transducers.

FAILURE MODES
AND ACCEPTANCE
CRITERIA: Uncertain, but believed to be similar to transducers.

REFERENCES: 89,92

4.3 Electrical Power Devices

GENERIC COMPONENT GROUP: Electrical Power Devices

4.3.1 GENERIC COMPONENT SUBGROUP: Switchgear

DESCRIPTION: Switchgear are devices covering switching and interupting devices and their combination with associated control, instrumentation, metering, protective and regulating devices; also assemblies of these devices with associated interconnections, accessories and supporting structures used primarily in connection with the generation transmission, distribution and conversion of electric power.

TYPICAL
MOUNTING: Switchgear is usually mounted in cabinets, panels or racks. These mounts are attached to surrounding structures or foundations.

SEISMIC
QUALIFICATION: Switchgear is usually qualified by testing. Current qualification programs impose IEEE 323-1974 and 344-1975. However, qualification programs conducted prior to the issuance of IEEE 344-1975 appear to have been a mixture of different testing philosophies. Initial seismic qualification tests, i.e., early 70's, were accomplished using swept sine and sine dwell tests. The qualification testing gradually evolved into the biaxial testing concepts endorsed in the latest versions of these standards. Since 1974, the seismic qualification of switchgear has used biaxial seismic simulators. Inputs forcing functions used to simulate earthquakes are derived from a location specific response spectrum. The two current methods used to develop signals to match site specific response spectrum are sine beat and shaped random.

AGING: Early qualification programs did not always consider aging. However, aging is being recognized as a variable which can contribute to malperformance of switchgear. Since 1974, IEEE 323 specifies the aging mechanisms to be considered. These aging mechanisms have been endorsed by the NRC.

FAILURE MODES AND ACCEPTANCE CRITERIA: Failure criteria are usually based on functionality of the equipment. Circuit breakers in particular must maintain their set state (open or closed), without chatter, and must be capable of proper change of state during the seismic event. It is interesting to note that very high acceleration transients (i.e., up to 100g) have been measured on the cases of some large circuit breakers during their operation. Such transients can affect adjacent instrumentation as well. In conjunction with this requirement, the criteria also specifies that the physical mounts should not fail.

REFERENCES: 7*, 8, 15, 28, 43, 45*, 52, 57, 59, 60*, 61, 64, 65, 68, 69, 80, 87, 119, 122, 123*, 124, 125, 127, 133, 243*, 244*, 276*, 306*

GENERIC COMPONENT GROUP: Electrical Power Devices

4.3.2 GENERIC COMPONENT SUBGROUP: Transformers

DESCRIPTION: A transformer is a static electrical device consisting of a primary winding and two or more secondary windings, with or without a magnetic core, for introducing mutual coupling between electrical circuits. Transformers are extensively used in electric power systems to transfer power by electromagnetic induction between circuits at the same frequency, usually with either stepped-up or stepped down values of voltage and current. Transformers can be incorporated as a component into an electric circuit or they can be stand-alone devices.

WEIGHT: Transformers can weigh from a few ounces, e.g., transformers used in miniaturized circuits, to tons, e.g., transformers used in power substations.

TYPICAL MOUNTING: Generally transformers are mounted by anchoring their case to a foundation. For transformers used in electronics, the foundation may be a circuit board. For medium size transformers used to step voltage, the foundation may be a cabinet, wall or floor. For large transformers used to step large electrical load the foundation usually includes reinforced concrete pads.

SEISMIC
QUALIFICATION: The preferred method for the seismic qualification of transformers is by test. The methods used are similar to those described for switchgear. For large transformers that cannot readily be tested, the qualification method is combined testing and analysis. Reference [7] describes a combined seismic qualification program for a large transformer. In this test program low level impedance tests were performed to determine the structural characteristics of a transformer. These results were used in conjunction with a mathematical model to predict the response of the transformer to a site specific earthquake.

AGING: Aging small and medium size transformers today follows the guidelines of IEEE Standard 323-1974 and 344-1974. Prior to these standards, aging was similar to the techniques used for switchgear. Aging requirements imposed on large transformers is uncertain. However, it is known that certain aging mechanisms can be significant in the insulation life.

FAILURE MODES
AND ACCEPTANCE
CRITERIA: The failure criteria imposed on transformers is functionality. Generally specified input and output voltages must be maintained without breakdown. In conjunction with this requirement, the criteria also specify that the physical mounts and attachments should not fail. The degree of this type failure allowed depends on whether functionality is preserved.

REFERENCES: 4, 7*, 8*, 28, 38, 57, 59, 62*, 63, 70, 76, 123*, 124, 243*, 244*, 276*, 306*

GENERIC COMPONENT GROUP: Electrical Power Devices

4.3.3 GENERIC COMPONENT SUBGROUP: Inverters

DESCRIPTION/
TYPICAL
MOUNTING: A device or system that changes direct current into alternating power. Usually inverters are an interconnected group of electronic components assembled into a system. The components are usually mounted in or on racks, cabinets and panels.

WEIGHT: Inverter systems usually contain electronic components with a substantial amount of iron. Consequently, the systems tends to be heavy, but compact.

SEISMIC QUALIFICATION: See switchgear.

AGING: See switchgear.

FAILURE CRITERIA: See switchgear.

REFERENCES: 337

GENERIC COMPONENT GROUP: Electrical Power Devices

4.3.4 GENERIC COMPONENT SUBGROUP: Emergency Diesel Generators

DESCRIPTION: Emergency diesel generators (DG) installed in nuclear plants provide energy for safety related systems. Basically the DG is a single or tandem diesel engine driving a generator. The engine is remotely controlled and the output energy is distributed by a switching system. Figure 4.3-1 shows a typical diesel generator system, which consists of a diesel engine on a test stand coupled to a generator. The DG is controlled by a series of instruments mounted in the control panel shown in Figure 4.3-2.

For large DG systems the engine block is a complex, welded structure with carefully machined surfaces. In the assembled engine, the block surrounds a large number of mechanical components, e.g., crank, pistons, rods, valves and etc. Attached to the block are the remainder of the mechanical and electrical engine components. The generator driven by the diesel engine is a rotor surrounded by field windings. The rotor is supported by the case structure of the generator which encloses the windings.

WEIGHT: The DG system is a compact assembly containing both electrical and mechanical components. The complete DG including the mounting skid can weigh in excess of 70 tons.

TYPICAL MOUNTING: The DG system including all monitoring and control panels and devices is usually mounted on a skid. The skid is a built-up structure using standard shapes including plates, and is appropriately mounted in an auxiliary building at the nuclear plant.

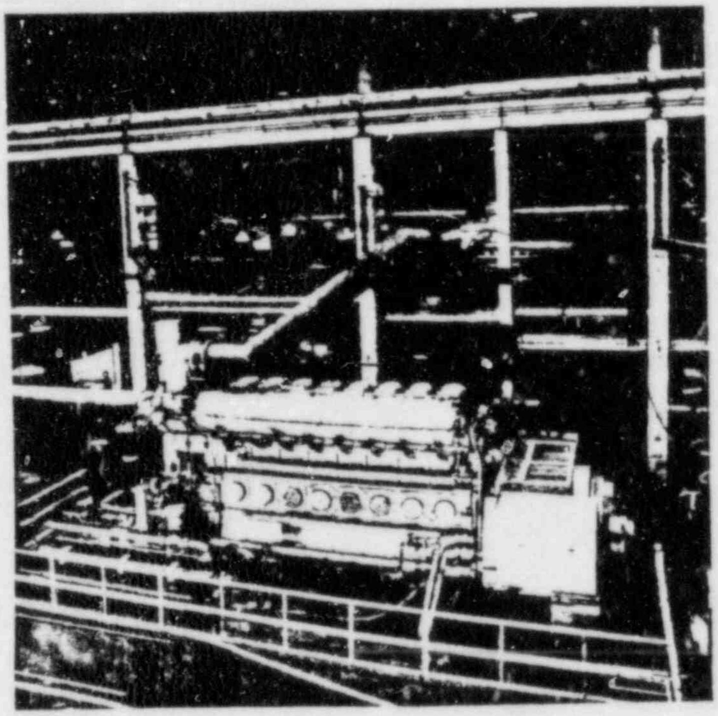

Figure 4.3-1 Diesel Engine on Test Stand at Engine Manufacturer's Facility (Ref. 272)

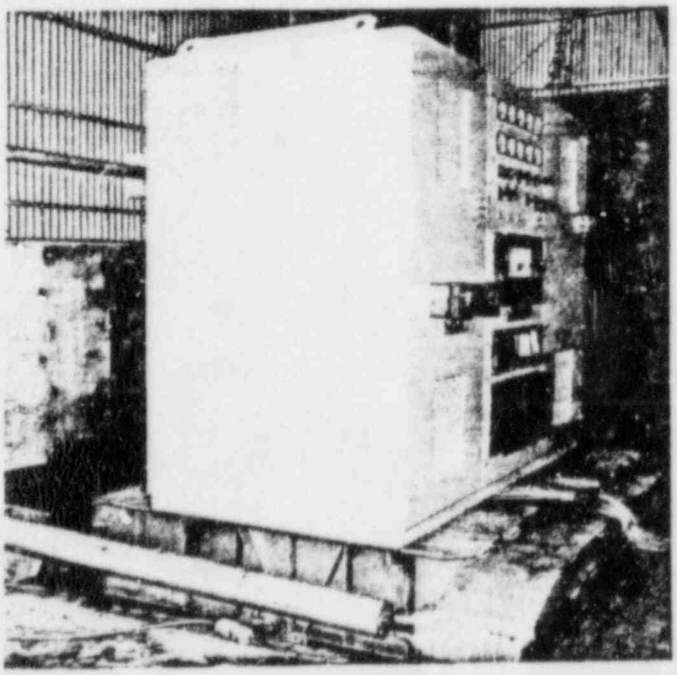

Figure 4.3-2 Control Panel on the Shake Table (Ref. 47).

The exact mounting technique, which can include isolation, depends on the specific site response spectrum.

SEISMIC
QUALIFICATION
METHOD: Seismic qualification of the DG has been of growing concern since 1967. Hagen[266, 267] reported that in 1967 the AEC (present NRC) had six requirements, and in 1971 had fifteen requirements on seismic qualification of diesel generators. Two methods have been used to qualify complete DG systems. Small DG systems have been qualified by shaking the complete engine coupled to a generator. Large DG systems have been qualified by combined testing and analysis. Total experimental qualification programs known to the authors have been used for relatively small DG systems. Complete systems, engine and generator, were mounted on a biaxial seismic simulator with statistically independent random inputs. During qualification testing the DG was operated at full load. The qualification input for the DG qualification programs known to the authors were plant specific.

Combined testing and analysis has been used to qualify a DG exceeding the weight limits of available seismic simulators. System qualification was accomplished by grouping the components into two categories:

a) Equipment that can be placed on a seismic simulator for dynamic testing.

b) Equipment that is too large/or heavy to be qualified by tests.

Two approachs used to qualify the large components are:

a) Model the system using results obtained from low level impedance (systems identification) methods.

b) Model the system using finite element techniques and suitable computer programs.

Both of the above techniques have been used to qualify DG's. References [48 and 49] detail the use of a finite element model to qualify a DG, and Reference [268] describes the use of low level impedance data to construct a model of a DG. Results from the mathematical models were used to establish input response spectra for components which could be qualified testing.

Comparison of References [48 and 268] illustrates basic philosophical differences between qualification programs performed in the U.S. and France. U.S. qualification programs essentially demand qualification by testing, if possible. French qualification programs permit more latitude for qualification by analysis. A French paper[48], states upon completion of a qualification program for the diesel engine and generator that: As a general result of these analyses, it can be seen that the seismic effects are very small compared with normal loads effects (mainly due to the engine excitation.) Based on these results, detailed analysis of each component is not required for seismic qualification, and sample models determined from experimental data would be sufficient.

AGING: Published reports indicate DG manufacturers have been careful to comply with the requirements in IEEE 323-1974 for Class 1E electrical equipment and IEEE 387-1977 for starting reliability. Thus all included components subject to aging must be tested accordingly.

FAILURE MODES AND ACCEPTANCE CRITERIA: Failure criteria for the DG appears to be based upon assigning acceptable stress limits to mechanical components and applicable functional criteria to the Class 1E electrical components. It is believed that operational reliability is imposed as a criterion for the diesel engine system as a whole unit.

REFERENCES: 48, 49, 57, 87*, 112, 177, 243, 244, 249, 266, 267, 268, 270, 271, 272, 306*, 337*

GENERIC COMPONENT GROUP: Electrical Power Devices

4.3.5 GENERIC COMPONENT SUBGROUP: DC Power Units

DESCRIPTION: A battery, as defined by IEEE 100-1977, is one or more cells electrically connected for producing electrical energy. The electrical energy is produced by a chemical reaction between the internal fluid, electrolyte, and the plates. The major battery system used in a typical nuclear power plant is located in a protected area on racks. This area is sufficiently isolated to protect the batteries from chemical sprays, sudden or extreme temperature changes, sudden pressure changes, or flying missiles. Modern computer systems can also contain batteries to prevent loss of memory or program during power interruptions. These batteries are often located inside one or more of the various system components.

WEIGHT: Individual batteries in the major DC supply system are compact devices. Their individual weight depends on size, but common industrial batteries often weigh over 1000 lb each. Because of their construction, the inertial properties of an individual battery is uniform. Individual batteries used in instruments to prevent loss of memory or programs are compact devices weighing less than 10 lb. The inertial properties of an individual battery are uniform.

TYPICAL
MOUNTING: The main DC power unit in a nuclear plant consists of a large group of batteries clamped to a rack. The batteries are interconnected terminal-to-terminal. The rack is a space frame structure fabricated from structural steel shapes.

SEISMIC
QUALIFICATION: Seismic qualification of a battery system appears to be guided by IEEE 344-1975 as specified in the IEEE 535-1979, "Standard for Qualification of Class 1E Lead Storage Batteries for Nuclear Power Generating Stations", and NRC criteria. No specific references were identified discussing qualification of seismic batteries for domestic nuclear plants.

Because of location, batteries are protected from all environmental stress except aging and radiation. Battery specimens to be used for seismic qualification can be assembled from cells of known age, or thermally aged cells. Reference [337] provides guidelines without supporting references for thermally aging batteries. Radiation stressing is usually of insignificant consequence. Batteries are located in areas expected to have radiation levels less than 1×10^4 rads.

FAILURE MODES
AND ACCEPTANCE
CRITERIA: Failure criteria for batteries are based upon their capacity for retention of electric charge. They are particularly sensitive to aging.

REFERENCES: 57, 87*, 243*, 244*, 274*, 276*, 337*

4.4 Valves

GENERIC COMPONENT GROUP: Valves

4.4.1 GENERIC COMPONENT SUBGROUP: Large Power Operated Valves

DESCRIPTION: Large power operated valves are used to control liquid and/or gas flow and to isolate flow from reactor systems. Large valves are typically constructed to include a heavy walled body which contains the internal mechanisms and an actuator offset above the body. In the design of valves for nuclear applications, care is taken to minimize the interruption to the flow so that corresponding vibrations and acoustic noise are also minimized. Three types of processes are used to operate valves: air, hydraulic, and electric. The most common method of valve operation is electric. Independent of the mechanism chosen, the valves are designed to permit manual operation.

TYPICAL MOUNTING: Valves are affixed to the piping system by either welding or bolting to flanges in place. Additional support is given to selected valves. Structural braces are used to support the valves; and, snubbers are used to provide additional support during some accident scenarios.

WEIGHT: Large valves are pressure boundaries and designed to comply with ASME pressure vessel codes and other applicable standards. These design requirements result in heavy, massive valve bodies. The weight is related to the pipe size. The operators are suspended above the valve body. Therefore, arrangement of valve body and operator results in two relatively heavy concentrated masses separated by a flexible structure. Large valves may weigh up to 5 tons.

SEISMIC QUALIFICATION: Large power operated valves have been qualified by testing, analysis, or testing and analysis. Generally, qualification by testing has consisted of mounting the valve on a shaker system (vector or independent biaxial), and then subjecting it to a simulated seismic input. The input is based upon sine beat or shaped random signals. Early qualification tests appeared to use swept sine or sine dwell. The rationale behind this type excitation is that a valve is a line mounted item, and as such is subject to rather low-damped, distinct resonant response. However, the exact frequencies for the resonances can vary considerably, depending on the structural boundary conditions of the pipe section in which the valve is mounted.

Analytical qualification appears to be based upon lumped mass beam models using sine beat or shaped random as input. However, the authors are aware of attempts to qualify valves using loss of coolant accident pressure histories combined with a seismic time history.

Combined testing and analysis have been used to qualify very large valves. Tests are used to verify calculated dynamic response characteristics of the valve or supply the needed terms for analysis. Using verified or experimentally supplied characteristics, the valve response is calculated using the appropriate response spectrum.

AGING: Because of their critical safety related nature, valves are subjected to a varity of aging stresses. The IEEE 382, "Qualification of Safety Related Valve Actuators", originally issued in 1972 and reissued in 1980, describes the aging requirements for valves. Hardening of polymer seal material is a special aging problem of concern. Figure 4.4-1 lists the qualification sequences for valves given in IEEE 382-1980. Based upon information available, consideration of synergistic effects has been limited.

FAILURE MODES
AND ACCEPTANCE
CRITERIA: The basic criterion underlying the qualification of valves is - they must work. Thus, they must operate from one extreme position to the other in a specified time, and cannot exceed a given leakage rate upon closure. Gauling of the valve stem due to excessive vibration displacement generally results in inability to meet either of the above requirements. Aging of seals usually results in excessive leakage. For each of the aging tests identified in Figure 4.4-1 criteria are established to assure proper operation of the valve. Furthermore, operational failure may result from malfunction of accessories such as solenoids, etc., which control the function of the valve itself.

REFERENCES: 47, 66, 87*, 113*, 114, 115, 142, 143, 229, 243*, 244*, 276*, 337*, 363

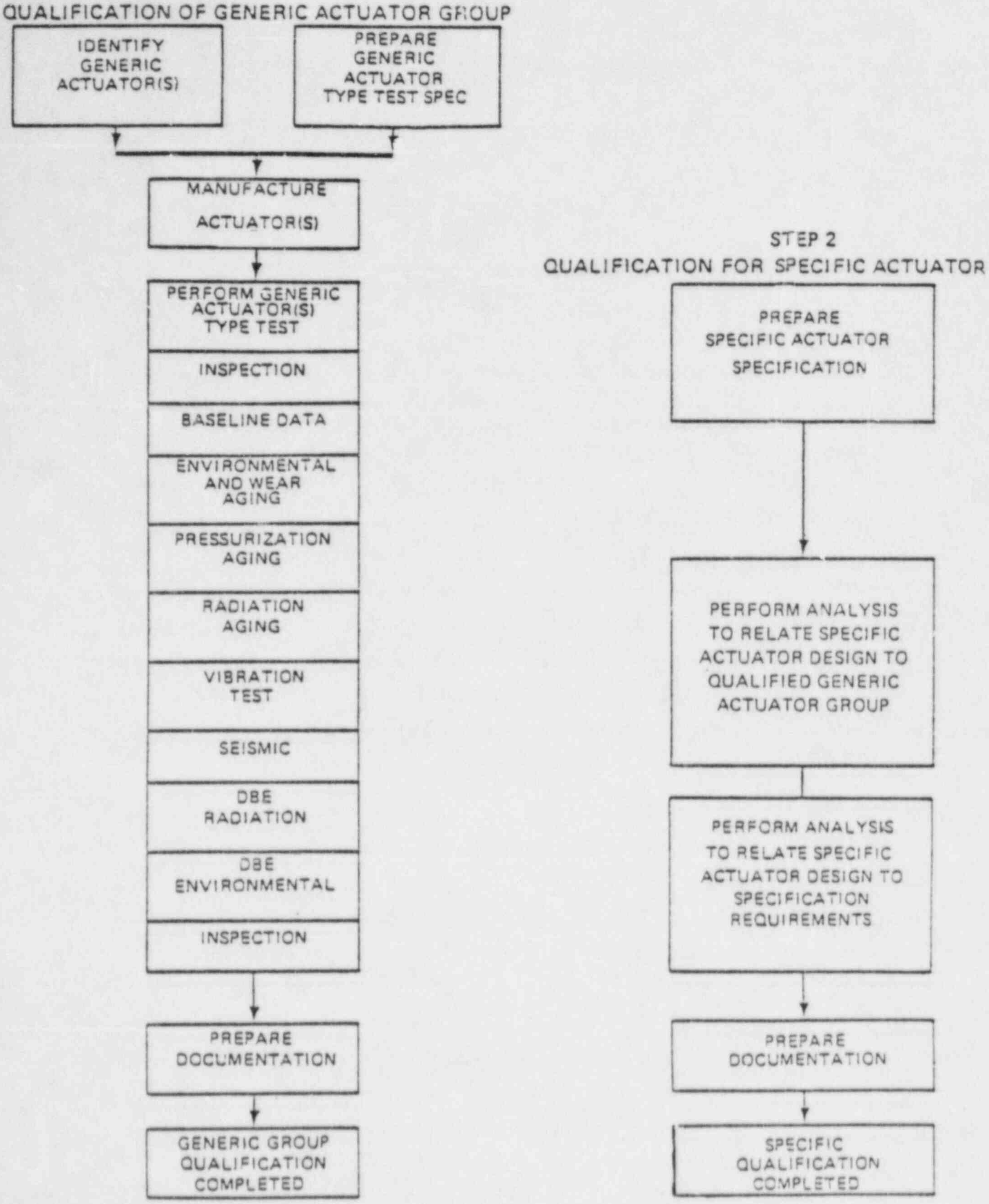

Figure 4.4-1 Flow Chart for Valve Actuator Qualification

GENERIC COMPONENT GROUP: Valves

4.4.2 GENERIC COMPONENT SUBGROUP: Relief Valves

DESCRIPTIONS: Relief valves are designed to open at a preset pressure and reseal when the pressure returns to a preset value. Relief valves accomplish their function by forcing a disk against a seat with a pretensioned spring. Preload of the spring governs the "pop off" pressure. The face of the disk and seat sealing surfaces are metal with surfaces polished to optical tolerances. Erratic operation of the valve or excessive vibration can damage these critical surfaces and cause the valve to leak or malfunction.

Main steam relief valves are long slender structures which look like an organ pipe. Other type of relief valves have a heavy body with an attached spring mechanism.

WEIGHT: Usually relief valves weigh less than 2000 lb. However, the exact weight and dynamic properties depend on their size and design.

TYPICAL MOUNTING: Relief valves are usually bolted in place. Flanges on the valves mate with flanges on the inlet and discharge (if used) piping. Usually no additional support is provided for a relief valve.

SEISMIC QUALIFICATION: Seismic qualification is by test or analysis. Initially qualification tests were performed using equivalent static loads to deform the valve. Current qualification tests include mounting the valve on a seismic simulator, input of various system loads (fast closure, lifting of seat, etc.) and simultaneously subjecting it to inputs derived from a sine beat or random signal.

AGING: To the authors knowledge aging is not considered in the qualification of a relief valve.

FAILURE MODES AND ACCEPTANCE CRITERIA: Failure criteria for valves usually involves demonstrating that the valve will respond as designed and reseat with an acceptable leakage.

REFERENCES: 10, 87*, 142, 363

GENERIC COMPONENT GROUP: Valves

4.4.3 GENERIC COMPONENT SUBGROUP: Check Valves

DESCRIPTION: Check valves are devices which prevent fluid flow in one direction, but permit fluid flow in the opposite direction. Check valves are installed inline in a pipe. The devices incorporate a flopper arrangement or a spring loaded disk.

WEIGHT: The vent valves used in a limited number of PWR reactor designs have a relatively massive body designed to withstand system pressure. The size of other check valves depends on the size of the pipe to which the valve is affixed. Thus, weights up to several hundred pounds are possible.

TYPICAL MOUNTING: Large check valves are bolted to mating flanges in the pipeline. Smaller check valves are installed inline with threaded connections.

SEISMIC QUALIFICATION: Current qualification tests mount the valve on a seismic simulator and then subject it to inputs derived from a response spectrum. Sine beats are also often used.

AGING: Unknown.

FAILURE MODES AND ACCEPTANCE CRITERIA: The failure criteria for check valves require demonstration of opening and closing operability with specified allowable leakage.

REFERENCES: 87

GENERIC COMPONENT GROUP: Valves

4.4.4 GENERIC COMPONENT SUBGROUP: Instrumentation Valves

DESCRIPTION: Instrumentation valves are small, self-contained devices used to switch, control and/or isolate the flow of fluid. As an example, a solenoid valve is used as the emergency fuel shutoff valve on the diesel engine used to power the emergency generator. Generally these valves are operated by air, hydraulics, or electricity.

WEIGHT: Instrumentation valves are light weight devices with bodies designed to withstand the expected environmental pressure. Typical weights are up to 25 pounds.

TYPICAL MOUNTING: Instrumentation valves are usually mounted in line with the pipe using threaded connection. However, these valves can be welded into the pipeline.

SEISMIC QUALIFICATION: Instrument valves are usually qualified as a separate item, but may be qualified as a component in larger systems. Hence, the qualification techniques are imposed on the overall system or on the individual components as appropriate.

AGING: Appendix E-3 of IEEE Standard 382-1980 provides a list of seven (7) operating performance criteria for this type of valve. However, this appendix is not part of the standard for qualifying this type of valve. Often instrumentation valves are aged in conjunction with an assembled system. The aging criteria specified for the system are then imposed on the valves.

FAILURE MODES AND ACCEPTANCE CRITERIA: The failure criteria for instrumentation valves require demonstrating operability with, usually, no leakage.

REFERENCES: 113*, 115, 131, 157*, 363

4.5 Piping

GENERIC COMPONENT GROUP: Piping

4.5.1 GENERIC COMPONENT SUBGROUP: Large Pipes

DESCRIPTION: The primary system of a PWR system contains two major categories of large pipes. Large pipes transport coolant from the reactor vessel to the steam generators, hot leg pipe, and large pipes, although smaller in diameter, transport fluid from the steam generator to the reactor, cold leg pipes. Typically, the hot leg pipes are approximately 38 in. (1 M) inside diameter; and, the cold leg pipes are approximately 28 in. (0.7 M) inside diameter. The wall thickness on the pipes can be in excess of 3 in. (8 cm). In addition to large pipes in the primary loop of a PWR, large pipes transport steam to the turbine in the secondary system. Large pipes also transport steam in a BWR system. The large pipes in a reactor system are fabricated from stainless steel or carbon steel clad with stainless steel. Depending on the reactor system designer, turning vanes may be installed in the pipes to achieve a specific flow distribution.

WEIGHT: The hot leg pipes weigh approximately 4000 lb/ft (6000 kg/m). The cold leg pipes weigh 2200 lb/ft (3300 kg/m).

TYPICAL
MOUNTING: Large pipes are restrained by embedded anchors, snubbers and restraints which are engaged by thermal expansion. These supports are designed to resist both seismic and loss of coolant loads.

SEISMIC
QUALIFICATION: Seismic qualification of large piping is usually accomplished using analysis. The mathematical models represent the piping system as lumped masses and the excitation as a response spectrum. This analysis provides reaction loads at the supports and the vessel. The necessary stiffness matrix elements are obtained using a finite element analysis, strength of materials formulae, or empirical data. The damping matrix elements are assumed to be equivalent viscous with a magnitude given by Regulatory Guide 1.61. The mass matrix elements include the mass of the structure and the internal fluid. The maximum response is obtained using the modal combination method described in Regulatory Guide 1.92. Outputs from the lumped mass model are used as input into ASME Code calculations and in special cases more detailed analysis of individual features of the pipes accomplished using finite element techniques. These analyses include finite element codes which allow for coupling the pipes to surrounding concrete structures. Also, the output from the lumped mass models is used as input to qualify snubbers.

Various tests whose results may be useful in qualification have also been performed to date. These include measurements made on pressurized and non-pressurized pipes, piping loops in hot and cold conditions, and with stresses well into the plastic range. It might be noted that measurements in general confirm higher values of damping than permitted in the Regulatory Guides at strain levels comparable to moderate earthquakes.

AGING/FAILURE MODES AND ACCEPTANCE CRITERIA: Large coolant pipes age from a variety of environmental effects. The aging effects include radiation, fatigue, corrosion and operation. Generally, these effects are incorporated into a failure criterion by using a very small value of the yield stress, i.e., 2000 psi.

REFERENCES: 9*, 10, 13, 15, 22, 26*, 29, 31, 87*, 130, 148, 174, 188, 190, 191, 222, 243*, 274*, 276*, 280*, 283*, 287, 338, 360*

GENERIC COMPONENT GROUP: Piping

4.5.2 GENERIC COMPONENT SUBGROUP: Small Pipes

DESCRIPTION: Different authors use various definitions for the separation between large and small pipes. Reference [87] defines small piping to be any pipe less than 8 in. (20 cm) diameter. Whereas the nuclear industry typically defines small piping to be any pipe less than 2 in. (5 cm). The definition given in Reference [87] will beused for this discussion for it best specifies the appropriate analysis techniques.

WEIGHT: The weight of small piping segments varies significantly depending on the material properties and wall thickness. The weight is further increased by the exterior insulation. This can significantly increase the strength requirements for the pipe and its hangers.

TYPICAL MOUNTING: Small pipes are mounted by anchors affixed to nearby surfaces and various types of clamps. Often these restraints must permit thermal expansion.

SEISMIC QUALIFICATION: Seismic qualification of small pipes is accomplished by analysis. Generally, the analysis uses either lumped masses and beam elements or the equivalent static techniques. If a lumped mass approach is used, the damping values assumed are consistent with the values given in Regulatory Guide 1.61. Piping in a nuclear plant is obviously important to safety. Reference [222] has identified that analysis methods and techniques are difficult to identify. For example, this reference states that for Class 1 instrumentation piping the analysis concentrated on lateral deflection and force evaluation curves; and, the model was unknown. Limited experimental justification was developed in the early 70's for piping analysis in nuclear plants. But, qualification in the late 70's was apparently by analysis.

AGING/FAILURE CRITERIA: The information reviewed did not generally state acceptance criteria. However, Reference [222] identified that for ASME III, Class 1 piping, for acceptance criteria the maximum stress was to be less than or equal to the ultimate and 2 times the yield stress.

REFERENCES: 9*, 10, 26*, 29, 31, 87*, 174, 188, 189, 190, 222, 239, 243, 274*, 276*, 280*, 360*

GENERIC COMPONENT GROUP: Piping

4.5.3 GENERIC COMPONENT SUBGROUP: Buried Pipeline

DESCRIPTION: In an emergency, buried pipelines carry important safety-related fluids from various storage sites to the location where they are needed. Typically, the pipes are layed in dug trenches and leveled using typical pipe laying procedures. The size of these pipelines can range from small diameter metal pipes to large concrete pipes, e.g., 19 ft (6 m) reinforced concrete tunnels which furnish seawater for the turbine condensers at Seabrook.[263]

WEIGHT: Buried pipelines are generally lightweight, flexible structures. However, they can be heavy as in the case of the buried concrete tunnel at Seabrook.

SEISMIC QUALIFICATION: Seismic qualification of buried pipelines is accomplished using analytical techniques. The analysis techniques vary from the application of sophisticated finite element codes to strength of materials equations. Independent of the type of analysis used, Ariman[237] noted that "There exists a large, but as yet mostly uncorrelated, amount of data and literature for the behavior and damage of buried pipelines during strong ground motion."

AGING: The adequacy of the seismic qualification of buried pipelines depends on material strength properties, e.g., yield strength and rupture strength. The amount of reduction in these properties by analyses to account for natural environmental degradation and radiation damage is uncertain.

REFERENCES: 34*, 40, 87*, 148, 233, 234, 237*, 238, 240, 241, 242, 274*, 276*, 295*, 296, 302

4.6 Pumps

GENERIC COMPONENT GROUP: Pumps

4.6.1 GENERIC COMPONENT SUBGROUP: Main Coolant Pumps

DESCRIPTION: The main coolant pumps in a reactor system circulate the coolant through the core of the reactor, to remove the heat from the fuel assemblies. The type and size of the coolant pump depends on the reactor design - BWR or PWR. For a BWR, the pumps operate at a system pressure of 1000 to 1300 psia, (70 to 90 bars); for a PWR, the pumps operate at a system pressure of 2200 to 2300 psia (150 to 160 bars). The temperature for both reactor systems is 530 to 575°F (280 to 300°C).

Figure 4.6-1 shows the design of the main coolant pump in a BWR. This type of pump is incorporated in the reactor vessel. The pump shaft is carried in two hydrodynamic bearings. The bearing in the reactor vessel is water-lubricated, and, the bearing outside the reactor vessel is oil-lubricated. The seal assembly consists of two sliding ring seals and one backup seal. The pump is connected to the driving motor by a coupling.

The reactor coolant pumps for a PWR shown in Figure 4.6-2 are vertical mixed flow, shaft sealed units driven by a single speed, water cooled motor. Shaft sealing is often accomplished by a throttle bushing and a mechanical seal. For the pump design shown, water is injected ahead of the throttle bushing; part of the seal flow passes into the pump volute while the remainder flows out along the throttle bushing and is returned to the seal water supply system. The outboard mechanical seal normally operates at a temperature of 95 to 100°F (35 to 38°C) and is designed for full reactor coolant system pressure. The main coolant pumps for a PWR system are designed to deliver approximately 100,000

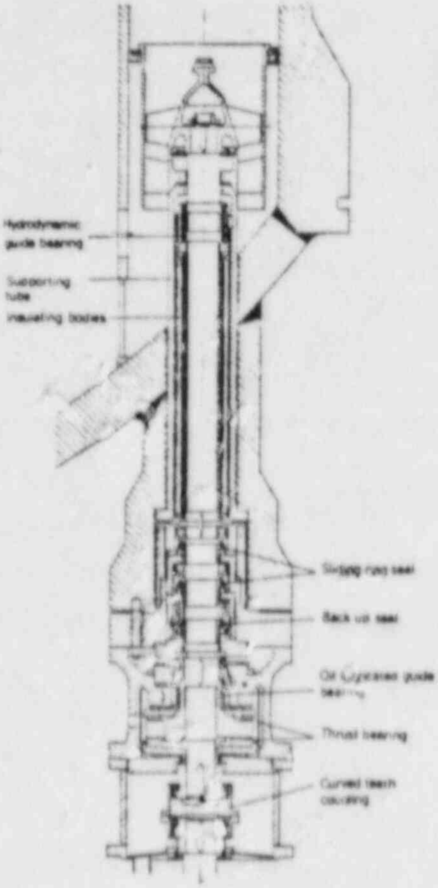

Figure 4.6-1 Main Coolant Pump for a BWR Plant

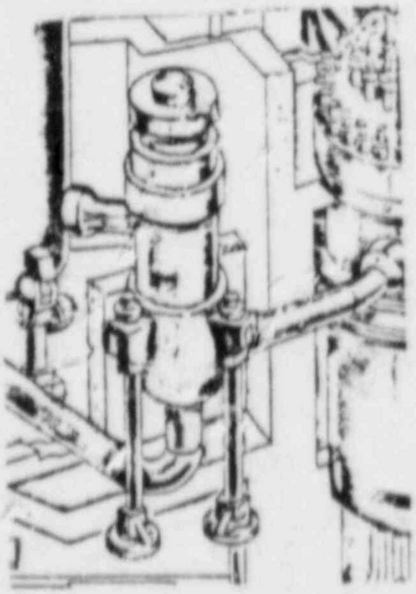

Figure 4.6-2 Main Coolant Pump for a PWR Plant

gal/min. of water. The motor required to power a single pump can exceed 10,000 hp.

WEIGHT: Reactor coolant pumps are large, heavy structures of up to several thousand pounds weight. The weight of the reactor coolant pump including the motor is not uniformly distributed. The motor is mounted to the pump housing and can extend more than 20 ft (6 m) vertically.

MOUNTING: Figures 4.6-1 and 4.6-2 show the mounting of a BWR and PWR main coolant pump. The pump for a BWR is integrally mounted in the reactor vessel. The pump for a PWR is mounted on the large pipe entering the reactor vessel. Also, supports are provided around the pump bowl, and often the motor is braced to a surrounding concrete structure.

SEISMIC
QUALIFICATION: Seismic qualification of the main reactor coolant pumps is by analysis. The analysis method uses the response spectrum applied to a lumped mass and beam model. The stiffness of various elements used to represent physical pump parts is derived using finite element techniques or strength of materials formula. The masses and inertial properties of the various elements are obtained from manufacturers information and drawings. Damping in the mathematical model is assumed to be principally equivalent viscous. The model input is a floor response spectrum if the pump is supported from the walls and/or floor, and response spectra obtained from a total NSSS system analysis. The response from the various seismic inputs is found using the square root of the sum of squares or the modal combination method described in Regulator Guide 1.92.

Test data were obtained in the early 70's which yielded the frequency and mode characteristics of installed pumps. It is generally understood that similar tests for verifying more recent analytical models have also been conducted in various plants, but the results have not been made available to the general community.

AGING: Main reactor coolant pumps are complex machines which require significant maintenance. At specific intervals the seal packing in reactor pumps is either repaired or replaced. The electrical components, e.g., motors, switches relays, etc., should be appropriately aged according to previously given data for electrical devices.

FAILURE MODES
AND ACCEPTANCE
CRITERIA: Failure of a pump basically occurs when it fails to deliver the specified amount of flow at rated pressure. Excessive stress or displacement of moving parts may be the cause of such malfunction. Reference [44] lists acceptance criteria based upon the maximum stress and displacement. For the failure criteria given, the maximum stress must satisfy ASME code allowables and the displacements must not cause interferences. Other references evaluated by the authors did not specify the failure criteria.

REFERENCES: 6, 9*, 15, 31, 44*, 87*, 213, 310

GENERIC COMPONENT GROUP: Pumps

4.6.2 GENERIC COMPONENT SUBGROUP: Medium to Large Pumps and Compressors

DESCRIPTION: Large horizontal and vertical pumps are used in nuclear plants. The horizontal pumps, including compressors, are usually mounted on a skid with the pump shaft aligned with the motor shaft. The vertical pumps have long-vertical shafts driven by aligned motors.

WEIGHT: The size and weight of the large pumps generally prohibit their qualification by tests.

TYPICAL
MOUNTING: Vertical pumps are usually supported by a flange near the top of the pump housing. Horizontal pumps are mounted on a skid. The skid is usually leveled and anchored to the buiding.

SEISMIC
QUALIFICATION: Seismic qualification of large horizontal and vertical pumps is by analysis. Two types of analyses have been used, response spectrum and equivalent static.

FAILURE MODES
AND ACCEPTANCE
CRITERIA: Failure criteria are based upon stress and deflection limitations between critical components.

REFERENCES: 87*, 179, 222, 243*, 244*, 276*, 310

GENERIC COMPONENT GROUP: Pumps

4.6.3 GENERIC COMPONENT SUBGROUP: Safety Related Pumps

DESCRIPTION: Small motor driven pumps are used in many safety related devices. For example, a small motor driven pump is used to supply oil to the bearings in a PWR main coolant pump. The small pumps are usually connected dirctly to the motor by a coupling.

WEIGHT: Small pumps are sufficiently lightweight to permit their qualification by testing, i.e., < 5000 lb.

TYPICAL
MOUNTING: Small pumps are mounted directly to the equipment on which they are used or the pump/motor is mounted on a baseplate. The baseplate is mounted to a machine or anchored to the foundation.

SEISMIC
QUALIFICATION: Seismic qualification for small pumps is by test. Based upon experience, current small pump qualification programs usually invoke IEEE 323-1974 and 344-1975.

FAILURE MODES
AND ACCEPTANCE
CRITERIA: Failure modes and acceptance criteria are based on functionality of the pump, similar to those previously described.

REFERENCES: 87*, 222, 243*, 244*, 310

4.7 Heat Removal System

GENERIC COMPONENT GROUP: Heat Removal System

4.7.1 GENERIC COMPONENT SUBGROUP: Heat Exchangers

DESCRIPTION/
MOUNTING: Various types of heat exchangers or condensers are used to remove heat from the reactor core. Condensers in a BWR system contain water which is in the primary coolant cycle. PWR systems use heat exchangers to remove heat from the core during normal shutdown operations and certain accident scenarios. The heat exchangers can be water-to-water or water-to-oil. The specific type depends on the application.

WEIGHT: Heat exchangers are usually large bulky devices surrounded by heavy walled vessels which meet ASME code standards. They may include total weights of several tons.

SEISMIC QUALIFICATION: Qualification is usually by analysis. Two types of analysis are known to have been used - equivalent static and the response spectrum technique.

AGING: Unknown.

FAILURE MODES AND ACCEPTANCE CRITERIA: Failure modes due to seismic excitation would be due to overstress or fatigue rupture, so that leakage would occur. Generally analysis must show that stress and fatigue levels are within acceptable limits.

REFERENCES: 77, 243*, 244*, 274*, 276*, 294

GENERIC COMPONENT GROUP: Heat Removal Systems

4.7.2 GENERIC COMPONENT SUBGROUP: Steam Generators

DESCRIPTION/MOUNTING: Steam generators are the primary heat exchangers used in PWR systems. These devices contain a large number of tubes encased by a shell designed to the ASME pressure vessel code and other applicable standards. PWR systems use two, three, or four steam generators. The specific number depends on the system design. Two styles of steam generators are in common use in PWR facilities. Of the three PWR manufacturers in the U.S., two use U-tube designs and one uses a straight tube design. The following describes the specific design features of each steam generator style.

A typical U-tube steam generator usually consists of two integral sections: an evaporator section, and a steam drum section. The evaporator section consists of a U-tube heat exchanger while the steam drum section houses moisture-separating equipment. The steam drum section is located in the upper part of the steam generator. The tubes are individually supported at intervals by horizontal support plates which are ported to permit flow of the steam-water mixture. All pressure-containing parts, with the exception of the Inconel tubes, are made of carbon or low alloy steel. All surfaces in contact with the reactor coolant are made of, or clad with, stainless steel or Inconel.

A typical straight tube, once-through, steam generator consists of three contiguous sections - nucleate boiler, film boiler and superheater. The generators are designed and manufactured in accordance with Section III of the ASME Boiler and Pressure Vessel Code. High pressure, high temperature reactor coolant flows into the upper head region of the steam generator through the straight Inconel tubes to the lower head. The tubes are supported at intervals by horizontal support plated which are ported to permit flow of the steam-water mixture.

WEIGHT: Steam generators are large heavy structures. A single steam generator can weigh more than 750 tons.

SEISMIC
QUALIFICATION: Steam generators are qualified by analysis. For qualifcation, the steam generator is modelled using lumped masses and beams. (This model is usually included in the overall seismic analysis of the reactor system). The dynamic input to the model is appropriate response spectra or time histories. Output responses are combined using recommended techniques. Currently, structural models using finite element computer codes are developed to analyze localized stresses and deflections subjected to the loads determined from the lumped mass beam models. However, early reactor system analysis used strength of materials formulae, elasticity solutions, and substantially less sophisticated computer codes. Some validating model tests are known to have been conducted recently in various plants but the results are not generally available.

AGING/FAILURE
MODES AND
ACCEPTANCE
CRITERIA: The components of a steam generator are metallic. The metals are chosen to resist radiation damage. The failure criteria are stress values which are established to include the effects of radiation damage, fatigue and other environmental effects which reduce the strength of the material.

REFERENCES: 6, 9*, 15, 17, 29, 31, 37

GENERIC COMPONENT GROUP: Heat Removal Systems

4.7.3 GENERIC COMPONENT SUBGROUP: Emergency Pump Drive Systems

DESCRIPTION/
MOUNTING: Emergency pump drive systems are diesel powered. These pumps are used to inject fluid into the core region during specific emergency scenarios. Often the pump drive systems are located in the diesel generator building.

WEIGHT: The emergency pump drive system is a compact heavy system. The combined weight of the diesel engine and pump can exceed 30 tons.

SEISMIC
QUALIFICATION: No information was found describing qualification of pump drive systems. However, the authors are aware of ongoing industrial programs for their seismic qualification. These programs use combined testing and analysis techniques. Analysis is used to qualify the large, heavy components and provide the required response spectrum input for the qualification of smaller components.

AGING: The current qualification programs being conducted on the pump drive systems include the aging mechanisms identified in IEEE 323-1974.

FAILURE MODES
AND ACCEPTANCE
CRITERIA: Failure criteria are identified consistent with the required functionality of a component. Stress is the failure criteria for components which can be severely strained during the imposed seismic event; functionality is the failure criterion for components which may malfunction during the imposed seismic event.

REFERENCES: 47, 243*, 244*

GENERIC COMPONENT GROUP: Heat Removal Systems

4.7.4 GENERIC COMPONENT SUBGROUP: Large Cooling Fans, Motors, Generators, and Compressors

DESCRIPTION/
MOUNTING: Large cooling fans are air circulating devices in which air is forced to circulate by a blower or blades coupled to an electric motor. Coupling can be direct or through a belt

drive. The electric drive motor used in a specific application depends on required horsepower, available power type, coupling attachment, and mounting requirements. Some electric motor designs have inertial switches for activating additional internal winding arrangements to start heavy loads.

WEIGHT: Fans are usually bulky, lightweight structures. Motors are compact, heavy structures. The weight of a motor varies depending on its horsepower and space allocations.

SEISMIC
QUALIFICATION: Large fans are qualified by analysis. However, the specific details of the analyses familiar to the authors are company proprietary. Motors are qualified by testing or a combination of testing and analysis. IEEE 334-1974, "Type tests for Continuous Duty Class 1E Motors for Nuclear Power Generating Stations", specifies acceptable seismic qualification methods. This standard invokes IEEE Standard 323-1974, "Qualifying Class 1E Electric Equipment for Nuclear Power Generating Stations" and 344-1971, "Guide for Seismic Qualification of Class 1E Electric Equipment for Nuclear Power Generating Stations".

Motor qualification in strict conformance with IEEE Standard 334-1974 may not adequately demonstrate functionality of the motor. The authors are aware of seismic qualification programs on motors which follow IEEE 344-1975 rather than the 1971 version. Motors have been qualified by combined testing and analysis. For this type of qualification the test usually refers to environmental stressing while analysis refers to the structural qualification.

The structural qualification of a motor is based upon a lumped mass beam model of the rotor and support structure. The bearing and the lubrication film are represented by a system of masses, springs and dashpots. The authors are aware of the attempts to include multilinear models for the springs and dashpots which model the bearings. The input motion to the motor is usually specified by a response spectrum. Specific motors used on the Alaska Pipeline Project are known to have received detailed attention.

AGING: Based upon experience, current motor qualification programs are guided by IEEE 323-1974. Abundant mechanical aging data exist from long term operation of industrial and power plant motors, but the degree that these data have been factored into the analysis is uncertain.

FAILURE MODES
AND ACCEPTANCE
CRITERIA: Failure criteria requirements for a motor are described in IEEE 334-1974. Structural response failure criteria are based upon specified deflection limits and stress. Testing should be conducted for the end of life condition of the motor insulation.

REFERENCES: 33, 57, 87*, 93

4.8 Air Conditioning Systems

GENERIC COMPONENT GROUP: Air Conditioning Systems

4.8.1 GENERIC COMPONENT SUBGROUP: Air Ducting

DESCRIPTION/
WEIGHT: Air ducts route air from supply units to remote locations requiring environmental control. Air ducts vary in size, shape and structural rigidity. Some air ducts are fabricated from thin, bent sheetmetal while others are fabricated from 1/4 in., or more, steel plate reinforced with strategically located structural shapes. Until recently heating and ventilating ducts were not protected from fire. However, requirements have been instituted which require certain air ducts to be coated with fire retardant material. This material can be of a cement nature or a foam which expands when heated. The addition of the fire retardant material significantly effects the seismic resistance of installed duct systems. It often lowers the resonance frequency of the duct system into the seismic excitation range. Ducts are often suspended from overhead hangers. This method of support permits the ducts to pass over other safety related equipment. Therefore, failure of the duct or hangars could jeopardize additional equipment.

SEISMIC
QUALIFICATION: Air ducts are principally qualified by analysis, although Reference [56] reports a test program evaluating the seismic resistance of ducts. Prior to the implementation of the requirement that certain safety related ducts be covered with a fire retardant material, seismic qualification was performed using equivalent static analysis. Since the implementation of the coating requirement,

qualification of ducts is accomplished using finite element codes with plate, shell, and beam elements. Input to the finite element model is the response spectrum at the support locations. Maximum responses are obtained using recommended procedures.

AGING: To the authors' knowledge no aging mechanisms are considered.

FAILURE MODES AND ACCEPTANCE CRITERIA: Air duct failure criteria are based upon acceptable stress values. Other criteria may be necessary depending on the proximity of other structures.

REFERENCES: 56, 87*, 297*, 299

GENERIC COMPONENT GROUP: Air Conditioning Systems

4.8.2 GENERIC COMPONENT SUBGROUP: Air Conditioning and Filtering

DESCRIPTION: Air conditioning and filtering systems are important for removing particulate contamination and providing proper environmental control. The air conditioning system can be a simple fan and motor as discussed in Section 4.7.4, or a complex refrigeration system with humidity controls. Filtering is usually done using room size units.

SEISMIC QUALIFICATION: Unknown.

AGING: Unknown.

FAILURE CRITERIA: Unknown.

REFERENCES: None.

4.9 System Support Facilities

GENERIC COMPONENT GROUP: System Support Facilities

4.9.1 GENERIC COMPONENT SUBGROUP: Cable Trays

DESCRIPTION/ TYPICAL SUPPORT: Cable trays used in nuclear power plants are steel (usually) ladder type structures. These trays support heavy bundles of wire held to the rungs in the cable tray by nylon tiewraps.

Cable trays snake their way from the initial to final termination point of nearly every wire in a reactor system. At intervals, the cable trays are supported from walls, ceilings or floors by locally suitable structures.

WEIGHT: Individual cable trays are relatively lightweight structures. However, when the cables are affixed to the cable trays, the combined structures can be quite heavy.

SEISMIC
QUALIFICATION: References [87 and 277], which describe the seismic review of selected nuclear power plants, draw no conclusion on the methods used to seismically qualify cable trays. Reference [87] states that "the seismic analysis (of cable trays) are similar to piping analysis in that floor spectra are applied at cable tray support points and responses are calculated and compared to deterministic design allowable stresses".

Reference [55] describes a two-phase seismic qualification program for cable trays. Phase 1 determines the design loads for the tray supports and trays; and, Phase 2 demonstrates seismic adequacy by test. The analytical method for the qualification of the cable trays cited in this reference uses a finite element computer code with beam elements. Structural consistency is insured by testing randomly selected cable trays. The trays are supported and loaded. The midspan deflection for various load increments is used to evaluate the natural frequency of the cable trays. This test continues until failure occurs by buckling or joint separation.

Reference [72] provides data where qualification can be performed by testing. Furthermore Keowen, et al[365] have carried out an extensive two-year test program involving virtually all types and configurations of cable trays and conduit raceways installed in nuclear power plants. The tests were carried out at high levels of response, up to and including some instances of support failure. These tests reveal that conventional designs have much higher values of damping than previously believed.

AGING: Unknown.

FAILURE
CRITERIA: Failure criteria are based upon allowable limits. The allowable limits described in Reference [55] considers the

function of the various parts of the system and the effects of exceeding these values on the functional requirements of the design.

REFERENCES: 55*, 56, 57, 72*, 87*, 195, 277*, 297*

GENERIC COMPONENT GROUP: System Support Facilities

4.9.2 GENERIC COMPONENT SUBGROUP: Fuel Storage Racks

DESCRIPTION: Fuel storage racks are space frames. These devices are used to support new and spent fuel assemblies in a secure, safe location.

WEIGHT: The fuel storage racks are bulky but relatively light. When loaded, the system becomes very heavy.

SUPPORT: Fuel storage racks are supported from the walls and floors. The upper portion of the fuel storage racks remain open for access by the handling equipment.

SEISMIC
QUALIFICATION: Based upon experience, fuel storage racks have been seismically qualified by analysis. The analysis methods include lumped masses interconnected by beams. Excitation is through the response spectrum.

FAILURE MODES
AND ACCEPTANCE
CRITERIA: Failure would typically occur by overstress or low cycle fatigue. Qualification must demonstrate response levels within appropriate limits.

REFERENCES: 228, 290, 293, 364

GENERIC COMPONENT GROUP: System Support Facilities

4.9.3 GENERIC COMPONENT SUBGROUP: Reactor Containment and Facilities Building

DESCRIPTION: The type of buildings used to house equipment at a nuclear plant is diverse. Buildings range from frames covered with sheetmetal to very thick reinforced, concrete structures. To be considered a subsystem, only smaller buildings and structures are included.

SEISMIC
QUALIFICATION: Each permanent building at a nuclear plant is evaluated for its seismic resistance where failure could interfere with safety. Building analysis includes interaction between the soil and building foundation. For seismic evaluation, the buildings are modelled as lumped masses interconnected by beams. The beams incorporate the dynamic structural properties of the structure as determined through a static analysis. The number of masses used to represent a building varies depending on the complexity of analysis requied. Energy dissipation in the model is usually included as equivalent viscous damping, with values taken from Regulatory Guide 1.61. Two types of excitation are used for analysis: time history and reponse spectrum. Time history excitation readily permits inclusion of nonlinear response mechanisms in the analysis. Response spectrum excitation requires modification to permit the inclusion of nonlinear effects.

Results from a simple model of the buildings are used to perform the detailed stress analysis. Analytical results are combined to determine maximum response values. Usually recognized techniques are employed. Some in situ experimental data have been acquired from both full scale and scale model items. These tests used both portable structural vibrators and explosives and achieved response levels in the range of 0.1 to 0.5 g. The results indicated high levels of damping and, in a number of instances, significant nonlinearities.

FAILURE MODES
AND ACCEPTANCE
CRITERIA: Acceptance criteria are based upon acceptable stress and deflection limits. The values selected are based upon results from recognized material test methods.

REFERENCES: 5, 9*, 10, 17, 20*, 22, 26*, 29, 41, 57, 73, 153, 154, 164, 173, 175, 185, 193, 196, 203, 221, 243*, 244*, 274*, 275*, 276*, 277*, 285, 288, 289, 291*, 294, 301, 305, 308*, 339, 341*, 343

GENERIC COMPONENT GROUP: System Support Facilities

4.9.4 GENERIC COMPONENT SUBGROUP: Internal Reactor Structures

DESCRIPTION/
TYPICAL
MOUNTING: Internal reactor structures support the nuclear core, provide flow control, and support reactor control devices. Figure 4.9-1 shows the internal reactor structures typical of a PWR. This figure shows that the reactor internals are composed of a shell-like structure, a core basket, which is suspended from the upper flange of the reactor vessel. The lower grid and flow distributor is attached to the bottom of the core basket. The entire group of fuel assemblies which form the core is supported by the lower grid assembly. The core is held in place by an upper structure called a plenum assembly. This assembly is a shell structure which surrounds a group of columns that contain the control rod guides and tube structure. The major internal reactor structures are fabricated from stainless steel and are assembled by bolting and welding. All structures are carefully inspected during each stage of this construction.

Prior to operation of a generic reactor design, the internal reactor structures are flow-tested as described in R.G. 1.20. Results from this test program provide the dynamic response characteristics of the internal reactor structure when excited by random or deterministic forces.

WEIGHT: The internal reactor structure is large and heavy. The core support structure plus the lower grid often weigh in excess of 50 tons. The upper plenum assembly can weigh in excess of 30 tons.

SEISMIC
QUALIFICATION: Seismic qualification of the internal reactor structures is based on analyses supported by test data on scale models in some cases. The structure is modelled using lumped masses and beams. The lumped masses represent the weight of the various structural components including the surrounding water; the stiffness properties of the beams are calculated using various types of analysis and represent the structural rigidity of the internal structures. The damping values

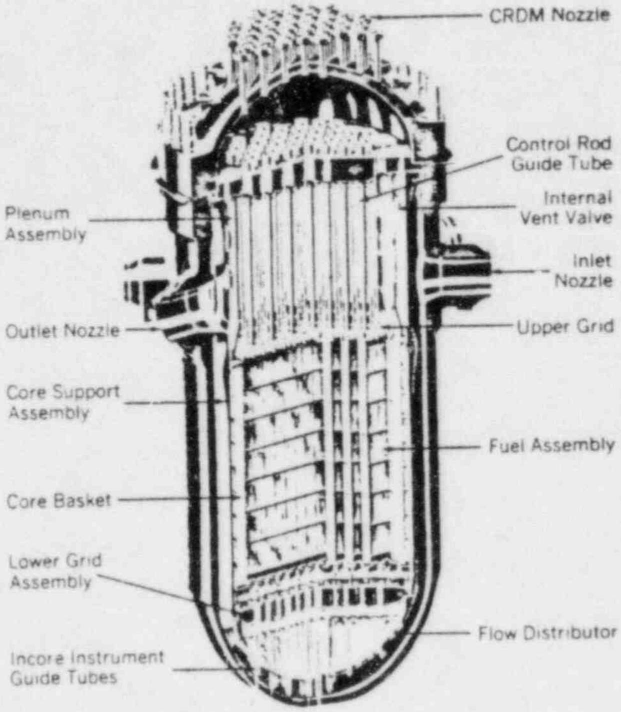

Figure 4.9-1 Reactor Pressure Vessel[260]

used in the analysis vary and are often adjusted to include fluid damping.

Seismic response for the complete mathematical model is predicted by response spectrum or time history methods. Results from the dynamic analysis are used as input for more detailed structural analyses. Test data obtained during the preoperational tests have been used to validate the analytical models. However, the results of this validation generally remain proprietary.

AGING/FAILURE
CRITERIA: The failure criteria used for the qualification of the reactor internals are based on stress. The stress limits are developed based upon fatigue considerations, radiation damage, and other material properties judged to be significant.

REFERENCES: 5, 10, 13, 15, 17, 22, 26*, 29, 41, 73, 85, 87*, 136, 169, 192, 194, 196, 283*, 292, 341*, 342*

4.10 Vessels

GENERIC COMPONENT GROUP: Vessels

4.10.1 GENERIC COMPONENT SUBGROUP: Large Vertical Vessels

DESCRIPTION/
TYPICAL
MOUNTING: Large vertical vessels are thin walled vertical storage tanks with a top and bottom, and generally anchored to a foundation.

WEIGHT: Generally, the tanks are lightweight for their bulky size, but the weight of the contents can be very significant.

SEISMIC
QUALIFICATION: Tanks are qualified by analysis using a finite element model excited by an appropriate time history or Housner's simple equivalent mechanical model method. Reference [284] describes the detailed analytical procedures to implement the Housner approach. The design process models the fluid in the tank with three masses. One mass represents the sloshing of the fluid, and the other mass represents the weight of the fluid in contact with the walls. The values and location of these masses, and magnitude of equivalent mechanical springs which connect these masses to the walls of the container are calculated

using given formulas. The appropriate inertia forces are determined using the masses, equivalent springs, and locations calculated as previously specified combined with the maximum seismic horizontal acceleration determined from the design response spectrum for zero period. This simple approach neglects any elastic mode response in the tank walls, and Coats[273] points out that this approximation is unrealistic. Kennedy, et al[87] conclude, for tanks analyzed by the Housner approach, that "all such safety related storage tanks in the reference plant should be reanalyzed accounting for the contribution of tank wall flexibility to seismic response." More recent data for design of tanks of various cross-sectional geometry is given in the review paper by Kana [333].

FAILURE MODES
AND ACCEPTANCE
CRITERIA: The failure criteria for large vertical vessels are based on maximum stress or buckling loads. The total stress must be based on a combination of convective or slosh load with the impulsive or inertia load of the nonsloshing part of the liquid. Qualification based on the single Housner method alone is usually inadequate because of underprediction of the impulsive stresses.

REFERENCE: 26, 29, 87*, 116, 165, 197, 230, 235, 236, 243*, 244*, 273*, 276, 277, 292, 306, 307, 333*, 345*, 346

GENERIC COMPONENT GROUP: Vessels

4.10.2 GENERIC COMPONENT SUBGROUP: Large Horizontal Vessels

DESCRIPTION/
TYPICAL
MOUNTING: Large horizontal vessels are thin walled tanks used to store large volumes of fluid, e.g., diesel oil at low pressure. These tanks are often supported by two or three saddle mounts anchored to a foundation.

WEIGHT: Generally the tanks are lightweight for their bulky size, but the weight of the contents can be very significant.

SEISMIC
QUALIFICATION: Qualification of horizontal cylinders has typically been performed by the Housner simple mechanical model method, in which the liquid surface is assumed to be in an equivalent

rectangular tank [346]. However, the previous statement about elastic wall response applies, and should be considered in any new designs.

AGING: Unknown.

FAILURE MODES AND ACCEPTANCE CRITERIA: The failure criteria are based on maximum material properties, i.e., yield and ultimate material strength.

REFERENCES: 26, 87*, 274*, 277*, 284, 292, 333*, 346*

GENERIC COMPONENT GROUP: Vessels

4.10.3 GENERIC COMPONENT SUBGROUP: Reactor Coolant System

DESCRIPTION: The reactor coolant system is composed of heavy walled, welded structures. The placement of the components and the type of components depends on the system operating principles. A BWR system has fewer major, individual components in the containment than does a PWR. Figures 2.4-1 and 2.4-2 in section 2.4 schematically show the individual components and their relationship to the containment.

TYPICAL MOUNTING: The reactor system is supported by means of devices which accommodate thermal growth, but restrain transient motion. In addition, the reactor vessel is usually supported on a grid system which minimizes stresses induced in the various components by transient motion.

SEISMIC QUALIFICATION: The seismic qualification of the reactor system is accomplished by analysis. However, tests have been reported describing the dynamic response characteristics of the reactor system to low level input forces. Two methods are used for the seismic qualification of the reactor system - time history and response spectrum. For both methods a lumped mass beam model of the entire system is developed. The lumped masses represent the weight of the system components including fluid; the system stiffness is represented by beam elements; and recommended damping values are used. The output from this model is used as input for a more detailed analysis of the individual components.

FAILURE
CRITERIA: Failure criteria are based on stress and the maintenance of critical structural tolerances.

REFERENCES: 9*, 15, 17, 26*, 29, 37, 41, 73, 87*, 135, 141, 153, 175, 192, 203, 213, 222, 223, 224, 243*, 244*, 276*, 280, 283, [illegible]8, 341*, 342*

4.11 Miscellaneous Components

GENERIC COMPONENT GROUP: Miscellaneous Components

4.11.1 GENERIC COMPONENT SUBGROUP: Snubbers

DESCRIPTION: Snubbers are a special type of shock absorber. They are designed to provide no resistance to motion for slowly moving structures, but to provide heavy resistance for rapidly accelerating structures. For example, these devices permit the unimpeded thermal growth of a structure but, in the event of an earthquake, provides instantaneous structural support. Snubbers are usually hydraulic type devices. Internal fluid, oil, is allowed to flow slowly through a valve mechanism but, in the event of an incident which causes the pipes to rapidly accelerate, the valve restricts the fluid flow. This action essentially locks the moving piston.

WEIGHT: Snubbers find extensive applications in nuclear facilities. For example, large snubbers are installed on pumps and generators; small snubbers are installed on pipeline important to safety. Hence, the weight of snubbers vary from a few pounds to tons.

SEISMIC
QUALIFICATION: Generally qualified by testing under simulated seismic motion conditions.

AGING: Unknown

FAILURE MODES
AND ACCEPTANCE
CRITERIA: Failure generally occurs by incorrect lockup or by leakage of hydraulic fluid.

REFERENCES: 182*, 312, 314, 315, 316*, 318

4.11.2 GENERIC COMPONENT SUBGROUP: Fuel Rod Assemblies

DESCRIPTION: Fuel rods containing pellets of Uranium dioxide are supported at each spacer grid by contacts integral with the walls of the spacer grids. The guide tubes are attached to the upper and lower end fittings, tying the assembly together. Usually the material in the guide tubes and the fuel rods are similar to minimize differential thermal expansion. Spacer grids are fabricated from slotted strips which fit together. The walls of a spacer grid form a square lattice which supports the fuel rods in two perpendicular directions. The lower end fitting positions the assembly in the reactor and supports the fuel assembly weight. Holes or slots in the fitting are provided for the control rods.

WEIGHT: An individual fuel assembly weighs between 1000 and 2000 pounds. The exact weight of a fuel assembly depends on the number of fuel rods. The dynamic properties of the fuel assembly are uniform.

SEISMIC
QUALIFICATION: Individual fuel assemblies are qualified by combined testing and analysis. Tests are performed to determine the dynamic characteristics of the fuel assembly, i.e., damping, frequency and mode shape. Also, tests are performed to determine the dynamic impact resistance of the spacer grids, guide tubes and fuel rods. These test results are used to form the structural matrices necessary for seismic qualification by analysis. Tests on fuel assemblies usually indicate that their structural characteristics are highly nonlinear. The nonlinearity is often attributed to the interaction between the fuel pin and spacer grid.

Seismic qualification of the fuel assemblies is accomplished by subjecting the experimentally formulated mathematical model to a required time history or response spectrum. The output is displacement and/or stress.

AGING: The fuel assemblies are fabricated from all metal components. The only aging mechanism usually considered is structural component changes resulting from normal wear or irradiation damage to the material.

FAILURE MODES
AND ACCEPTANCE
CRITERIA: Failure criteria are based upon strength properties of the fuel pins and the crushing strength of the spacer grids. Usually manufacturers permit no damage to a spacer grid resulting from a seismic event.

REFERENCES: 87*, 144, 145, 168, 341*, 342*

GENERIC COMPONENT GROUP: Miscellaneous Components

4.11.3 GENERIC COMPONENT SUBGROUP: Control Rod Drive Mechanisms

DESCRIPTION: The control rod drive mechanism consists of a device to force either rods or plates into tubes or slots in a fuel assembly. The plates or rods absorb neutrons in the reactor core and control the rate of reactivity. The principle used for the control rod drive depends on the reactor type. Some control rod drive mechanisms are hydraulically driven and others are electrically driven. Both types of mechanisms are designed to automatically insert the control rods in case of power failure.

SEISMIC
QUALIFICATION: Seismic qualification of control rod drive mechanisms is accomplished by either test or analysis. Reference [85] describes seismic qualification of a reed switch in a control rod drive by testing. The control rod drive in the test is mounted on the base of a vector type simulator. The input simulates the required seismic input

The more common method of qualifying the control rod drive is by analysis. The drive is modelled by a lumped mass beam type model. The model is excited with the appropriate response spectrum obtained during the analysis of the reactor system.

AGING: Unknown.

FAILURE
CRITERIA: Unknown.

REFERENCES: 9, 85*, 87*, 147, 178, 243*, 244*, 276, 341, 342

5.0 ANOMALIES IN QUALIFICATION METHODOLOGY

The previous sections of this report have been compiled to present available information on the state-of-the-art for general qualification. An evaluation of this information was performed to seek out deficiencies and anomalies that can ultimately affect the validity of equipment qualification. A summary of the results of this evaluation for general methodology will be presented in this section, while results for equipment subgroups will be given in the next section. Emphasis in both cases is on anomalies or uncertainties that exist for seismic qualification but the influence of other environmental factors is included as well. These results are based not only on the referenced literature, but also on conversations with other experts in the field. Only the most significant anomalies will be considered here, and only the most pertinent references will be specifically cited. However, it is understood that information from many of the references forms the basis for the anomalies discussed.

It should be emphasized that the definition of the word "anomaly" as used herein includes the occurrence of a noted unexplained potential variation of results in qualification. It is paramount to recognize that these anomalies may or may not be significant in influencing the validity of the qualification process. Furthermore, each cited anomaly does not apply to qualification in general, but only to certain cases. As a further clarification, it is extremely important to point out that this discussion of qualification methods anomalies must not be taken to imply that any of the equipment qualification performed to date is necessarily inadequate. To the contrary, early seismic test programs recognized that the test methods did not necessarily provide a close simulation of the actual seismic event and, consistent with a good engineering practice, qualification testing was accomplished with a degree of conservatism which was judged sufficient to cover the uncertainties. In fact, further study of the anomalies will help reveal to what degree conservatism has indeed been present.

5.1 Qualification By Testing

5.1.1 Uncertainties in Use of Response Spectrum

The response spectrum has been used to describe the action of an earthquake on a structure since the early 1930's.[323] This adaptation of the shock spectrum parameter has found wide acceptance in analytical prediction of seismic response of structures. It was a natural development that has become the preferred parameter for specifying the excitations to be used for testing of equipment. However, test equipment having the capability of producing motions whose TRS closely resembles a given RRS has become available only much more recently. In the interim, various simpler approaches including the use of sine dwells, decaying sines, and sine beats were employed. Various combinations of these methods were used to simulate ground level motion with broad frequency content, as well as floor motions with limited frequencies filtered by building resonances. Slowly, the trend has been to reserve these methods for synthesis of floor motions, and to employ shaped signals of broad band random motion for ground level motions. This path of development has led to the present existence of a number of uncertainties associated with the simple requirement that a TRS envelope the RRS in a typical specification.

Currently, much confusion and outright disagreement exists on the details of how signals may be synthesized such that the resulting table motion will provide a TRS which envelopes a given RRS. This problem has been aggravated by the nonuniqueness of a response spectrum, in that many time histories can be utilized to produce a TRS that envelopes a given RRS. It is further compounded by the absence of any quantitative specification of tolerance on the enveloping process. Thus, it is possible to produce a motion whose TRS envelopes the RRS as required, but violates the spirit of the specification because basically an inappropriate time history is employed.

Kana[86] has discussed the adequacy of test signals at some length. Figure 5.1-1 shows a case where the TRS was within ±3dB of the RRS. However, in Figure 5.1-2 the power spectral density shows negligible energy input above 10 Hz. A conclusion was drawn in the example that excess of frequency content below 10 Hz does not adequately

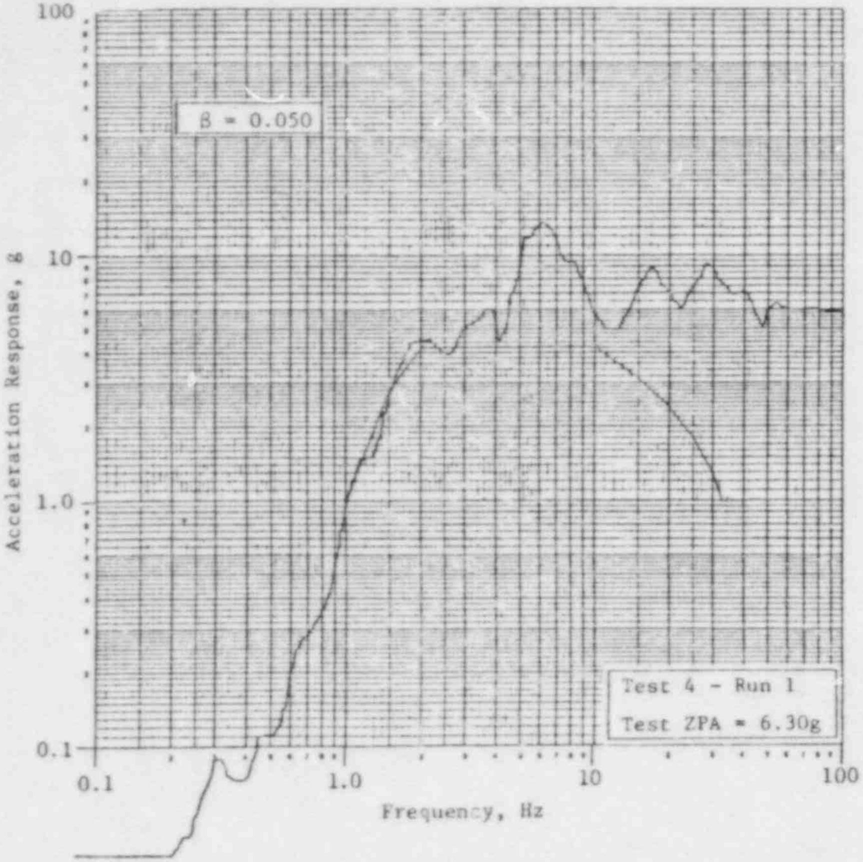

Figure 5.1-1 Response Spectrum

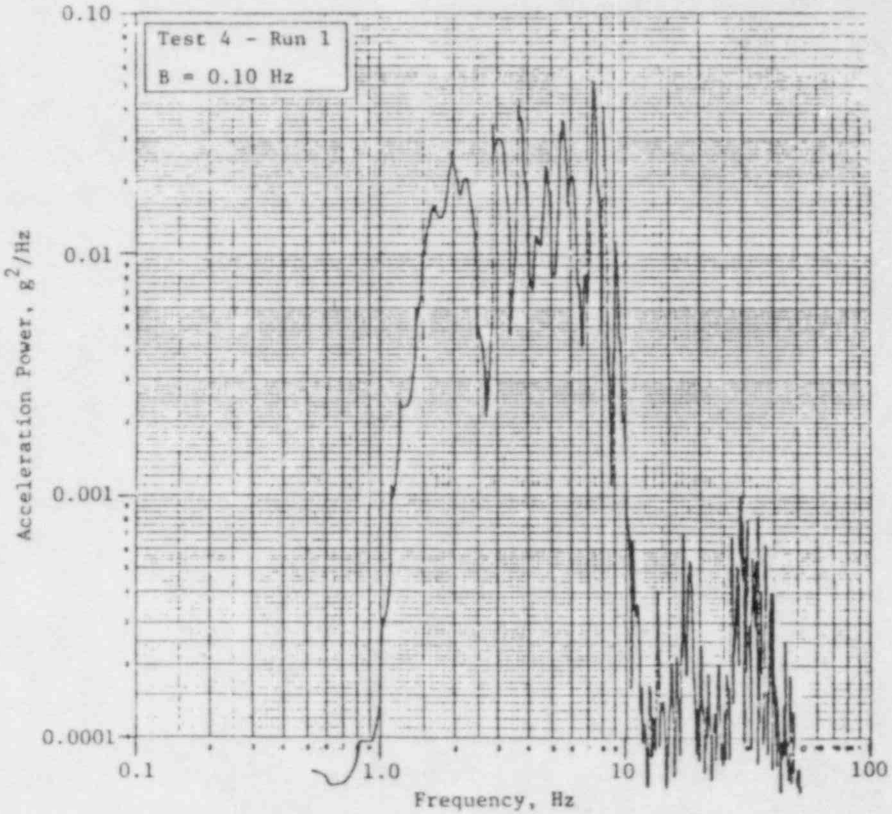

Figure 5.1-2 Time-Average Power Spectrum

PARAMETERS WHICH DESCRIBE GROUND ACCELERATION
(a_{1y}), Y-Z EXCITATION

make up for a lack of frequency content between 10 and 30 Hz (note that amplification of the TRS above the zero period acceleration, ZPA, implies that frequency content must be present in the corresponding frequencies). An extreme example of a sine dwell enveloping a broad band signal is given in Figure 5.1-3. Here energy is present in the sine dwell only at 3 Hz, in spite of the fact that its TRS envelopes the RRS. For such a case it is obvious that multiple modes present at other frequencies in the equipment will not be excited with proper amplitudes and phases. However, no evidence is available as to just how close an enveloping of the RRS by the TRS is necessary to produce an adequate test. Much recent discussion on this subject has tended toward the necessity of further requirements on adequacy of frequency content and stationarity of simulated motions. That is, frequency content should be present at all frequencies where amplification of the RRS over the ZPA exists, and the content should be statistically present for the entire duration of the earthquake event. The methods for assuring that this has been accomplished remain uncertain. It appears that the response spectrum is a rather coarse parameter for development of desired signals. Nevertheless, Unruh and Kana[202] have shown where additional development of an equivalent power spectral density can be of considerable help. Furthermore, the early use of sine dwells or sine beats at resonance frequencies is recognized to produce a quite conservative test for those cases where resonances of an item are completely established. However, sequential use of such dwells does not provide adequate stationarity for representing a general ground level simulation.

Many types of component signals can be summed to form an aggregate time history whose TRS hopefully envelopes a specified RRS. Until the advent of small dedicated computer systems the signal manipulation adjustments necessary to duplicate a particular response spectrum were done manually. The interactive process of forming a signal whose response spectrum matches the required response spectrum was labor intensive. However, laboratories can now perform the necessary signal manipulations in a few minutes using computers to iterate and adjust a random signal. Unruh[269] describes the computer software and hardware for generating a time history signal matching a

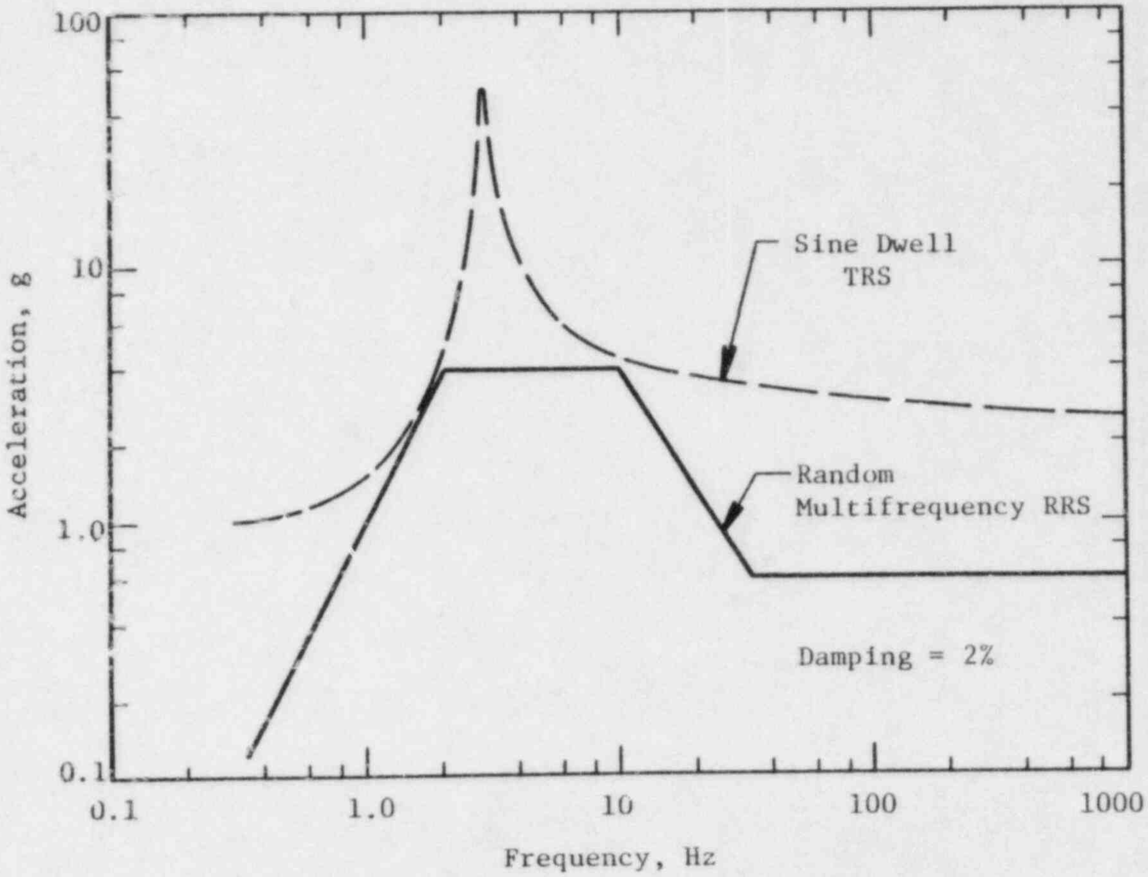

Figure 5.1-3 Envelope of Random Multifrequency Required Response Spectrum with 2.5 g, 3 Hz Sine Dwell TRS

specific response spectrum. He has developed appropriate software for commercially available minicomputers. Preprogrammed systems including hardware and software are available for shaping and combining random information to envelope a given response spectrum. In spite of all this sophistication, however, excess enveloping of the RRS by the TRS at higher frequencies can occur because of the inherent presence of harmonic content generated by nonlinearities in typical hydraulic actuation systems, or by rattling of loose parts or panels in the specimen and table.

Measurement of zero period acceleration (ZPA) is another common uncertainty associated with the use of the response spectrum in testing. It is not unusual to experience test ZPA's much larger than that specified on the RRS, even though significant efforts are made to match the correct frequency content and allow for complete stationarity. However, extraneous frequency content caused by nonlinearities, as described above, will cause the test ZPA to occur at higher than desired frequencies. In fact, rattling of loose parts can push the ZPA to very high frequencies (i.e., > 500 Hz). Thus, some method of filtering or reduction of the data is necessary to assure that the correct amplitude of motion has occurred in the amplified region of the specified RRS. Furthermore, excess enveloping and a high ZPA obviously may lead to premature failure of a component.

5.1.2 Effects of Cross Coupling

Structural components and equipment generally possess characteristics such that their dynamic response principal axes do not coincide with the apparent geometric principal axes, i.e., cross coupling exists in the specimen. In the past this has been recognized, and it has been stated that three axis excitation provides the best simulation as a result. However, at the same time, one or two axis simulation has been allowed, so long as conservative results can be assumed. Specifically, IEEE 344 states:

> "The minimum is biaxial testing with simultaneous inputs in a principal horizontal and the vertical axes. Independent random inputs are preferred and, if used, the test shall be performed in two steps with the

> equipment rotated 90° in the horizontal plane for the second step. If independent random inputs are not used (such as with single-frequency tests), four tests should be run. First, with the inputs in phase; second, with one input 180° out of phase; third, with the equipment rotated 90° horizontally and the inputs in phase; and, finally, with the same equipment orientation as in the third step but with one input 180° out of phase."

Figures 5.1-4 and 5.1-5 show schematically the concepts of dependent and independent biaxial testing, respectively. In addition, as is sometimes specified, the specimen is oriented at 45° to the horizontal excitation direction. The latter addition is a further complication to the uncertainties that already are inherent in the biaxial versus triaxial excitation question. No data are known to exist for comparing the responses in one kind of test to another. There is some tendency to say that triaxial simulators will eliminate such uncertainties. However, there is no evidence that proves that other types of testing are not conservative, and therefore more desirable from the point of view of using a much less expensive test system. Furthermore, there is no criterion specified on the degree of cross-correlation that is allowed for a machine to qualify as an independent axis testing device. Chen [352] has shown limited evidence that samples of actual earthquakes show a cross-correlation of 0.16 or less at ground level. However, torsional cross-coupling in buildings may cause high correlation at certain frequencies at elevated floor levels.

Testing of line mounted equipment introduces another aspect of uncertainties in cross coupling. In particular, valves generally are mounted in the middle of supported pipe sections, so that significant torsional rocking exists for transverse motion. Some present test specifications prescribe tests where the valves are mounted by flanges to rigid bookends, and are excited by translational motion. In such a case, the torsional rocking is ignored, unless allowed for by increased input levels. Other specifications require that the input motion be of a sine beat type to simulate response at a narrow pipe resonance, and be of sufficient amplitude to include the effects of torsion. This is

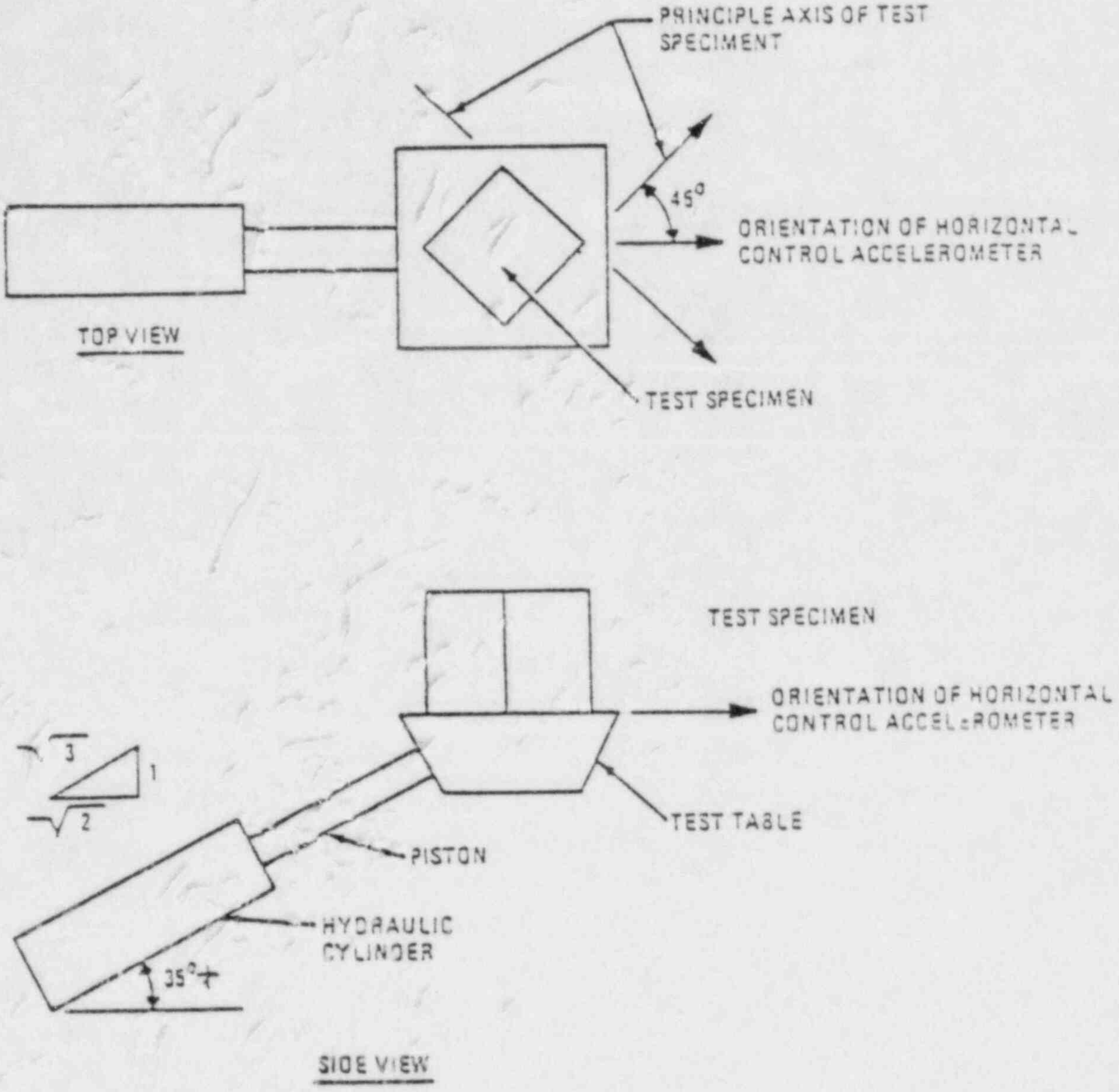

Figure 5.1-4 Schematic Diagram of Test Setup Machine for Dependent Random (Test Specimen Also Oriented at 45°)

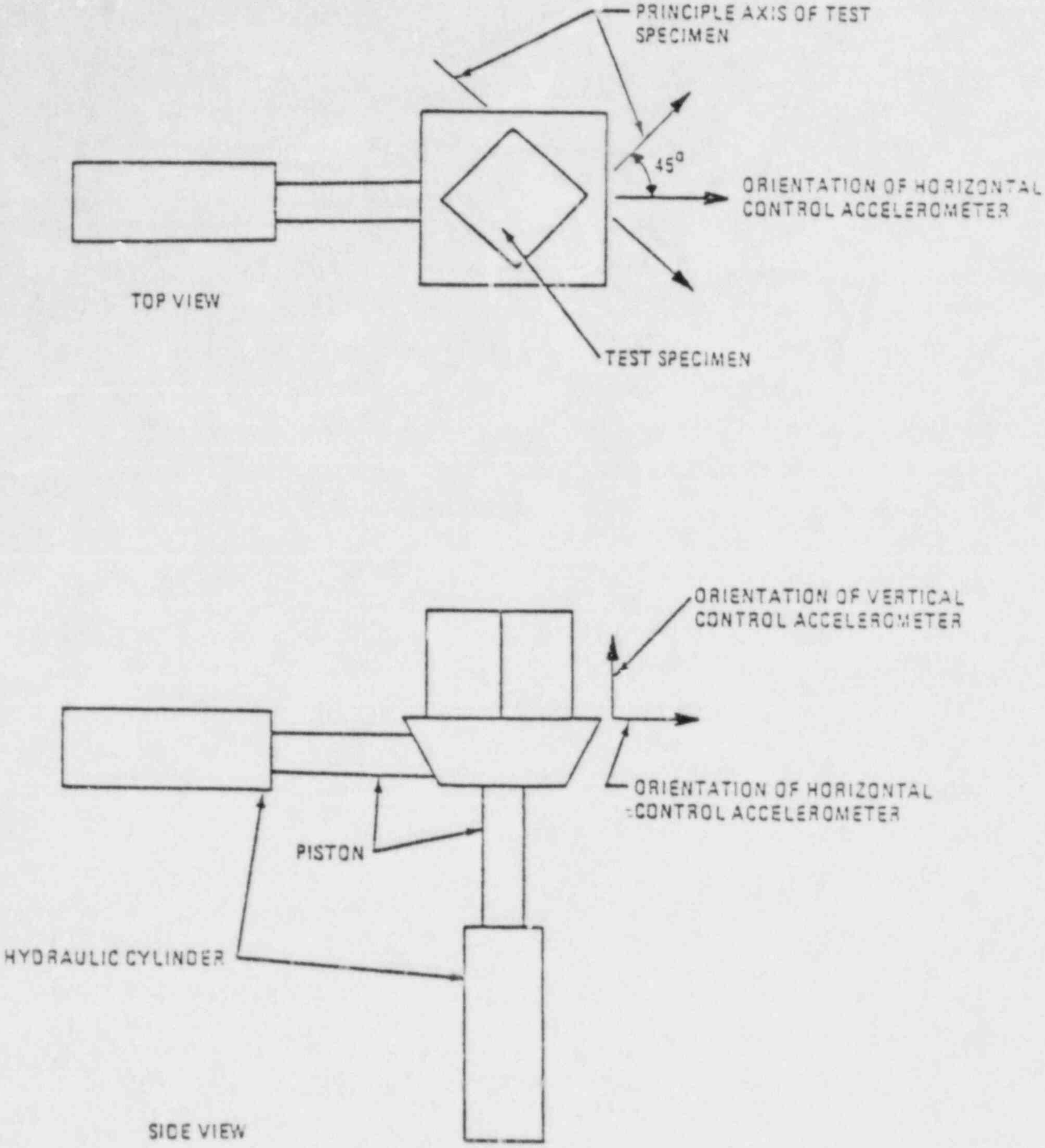

Figure 5.1-5 Schematic Diagram of Test Setup Machine for Independent Random (Test Specimen Also Oriented at 45°)

usually referred to as a RIM (Required Input Motion) test. However, no published data are available to show which method provides an adequate qualification with the least amount of conservatism.

5.1.3 Comparison of Test Severities

It has been mentioned previously that early qualification tests attempted to produce earthquake simulations for both floor level and ground level tests by means of narrow frequency band techniques such as sine dwells, sine decays, and swept sine. Later, sine beat techniques emerged. Usually, these methods were recognized to be reasonable for representing floor level motions, but not as good for ground level tests which include broader frequency content. Sequential application of the signals at various frequencies, including resonances was used to simulate the presence of the broader frequencies. More recently, shaped random signals, which are synthesized by multiple bands of random data, and include RMS amplitudes which build up, hold for a specified time, and then decay similar to an actual earthquake, are used for a much better simulation of the ground level motion. In all of this, a pertinent question arises as to whether the previously conducted tests are conservative (more severe) compared to the more recent and complex tests.

The use of sine beat testing also presupposes the ability to establish resonances in a given system. References [60, 119, 132] demonstrate the application of the sine beat method for signal synthesis. Specific criteria include:

1. A continuous-sweep frequency search using a sinusoidal input of approximately 0.2 g shall be performed to determine the natural frequencies of the equipment up to 25 Hz.
2. A sine beat test shall be performed at each natural frequency found by the frequency search.
3. In addition, sine beat tests shall be performed at frequencies other than the natural frequencies to cover the spectrum up to 25 Hz.
4. A sine beat test at any natural frequency shall consist of a train of 5 beats, the pause between beats to be at least two seconds. There shall be a 5 cycles/beat input acceleration.

The philosophy behind this test method is that the equipment will experience at least as much (or more) damage (malfunction potential) than it will in any more representative multifrequency environment. This philosophy is typical of that required for formulating any type of vibration equivalence test. It suffers from the uncertainty that one cannot always identify the exact form of damage that will occur in a given case. Furthermore, all resonance frequencies cannot always be accurately determined. This is especially true for instrumentation or devices whose internal mechanisms are unknown. Thus, it is usually better to design a test which represents the excitation as close as possible, (i.e., frequency content, stationarity, amplitude, etc.), and let the failure mechanisms be activated accordingly.

In order to compare severities of previous tests to more recent tests, some form of failure parameter must be developed or at least assumed. Fatigue, mechanical gauling, electrical failure, chattering of relays, premature operation, and leakage of valves are all examples of a multitude of typical failure mechanisms that can occur in equipment. Beyond this, a relationship between the damage or failure mechanism and the dynamic response parameters (i.e., displacement, stress, acceleration, etc) must be developed. Thus, the matter of establishing vibrating equivalence is an extremely complex task.

Curtis[198] and Fackler[199] have evaluated equivalence between tests using sinusoidal, swept sine and broad band random input. Table 5.1-1 shows the necessary equivalence relationships to interchange input excitation. This table shows that there is no universal equivalence between sine dwell, swept sine, and random. The relationships between the various combinations are significantly different and depend on the postulated failure mechanism. In addition, equivalences based on producing identical failures such as fatigue have widely differing values according to such factors as damping, stress level, and material properties. The equivalence relations in Table 5.1-1 provide one approach which can be considered between various methods of simulating an earthquake.

The problems faced with establishing equivalence is stated by Curtis[198] "Instead of simulating a service environment with a test environment that resembles the basic characteristics of that environment, it is sometimes necessary to substitute a method which is

TABLE 5.1-1 EQUIVALENCE RELATIONSHIPS BETWEEN SINUSOIDAL SWEEP, SINUSOIDAL DWELL, AND BROADBAND RANDOM

Basis of Equivalence	Test Condition	Equivalent Test Methods		
		Sinusoidal Dwell	Sinusoidal Sweep	Broadband Random
Fatigue	Level	$\ddot{S}_o$	$\ddot{S}_o$	$W = \frac{KQ}{f_n} \ddot{S}_o^2$ $0.19 > K > 0.056$
	Duration	T_c	$T_s = K T_c$ $0.24 < K < 2.85$	$T_r = T_c$
Peak Response	Level	$\ddot{S}_o$	$\ddot{S}_o$	$W = \frac{2 Q\ddot{S}_o^2}{9\pi f_n}$
Root Mean Square Response	Level	$\frac{\ddot{S}_o}{\sqrt{2}}$	$\frac{\ddot{S}_o}{\sqrt{2}}$	$W = \frac{Q \ddot{S}_o^2}{\pi f_n}$
Energy Dissipation	Level	$\ddot{S}_o$	$\ddot{S}_o$	$W = \frac{Q \ddot{S}_o^2}{\pi f_n}$
	Duration	T_c	$T_s = \frac{2 T_c}{\pi}$	$T_r = T_c$

$\ddot{S}_o$ = peak sinusoidal excitation level
W = acceleration spectral density
T_c = duration of sinuoidal dwell test
T_s = time to sweep half-power bandwidth of a resonance
T_r = duration of random test
K = constant
Q = peak amplification factor
f_n = resonant frequency
b = measure of slope of σ-N curve
n = damping-stress exponent

different in character, but is equivalent in its effect on the test specimen. When a test is equivalent to another, the two tests should produce equal effects on the test component. That is, the damage caused by each of the two methods should be equal. This is usually not possible to accomplish if more than one effect is to be simultaneously simulated. For example, it may be possible to simulate the fatigue damage caused by a random environment with a sinusoidal sweep but it is unlikely that the same sinusoidal test can simulate both the fatigue and the effects of random environment have on the functional performance of the test item. Therefore, equivalence between two methods implies the equivalence of the single most damaging effect on the environment."

From this statement one can infer that for equivalence to be established for a complex specimen which is subject to two different vibration fields, the acceptance criteria must define the damage criteria in terms of the dynamic response of the structure and its effects on the most likely form of failure. For example, acceptance criteria for a relay often states that the device will not change states during the seismic qualification test. This is a statement of required functionality of the component and is adequate only for an exact simulation of the excitation. But, this statement does not provide a continuous link between the damage criteria defining functionality and the dynamic response of the structure, and therefore is insufficient for application to an equivalent test. A more precise definition of this acceptance criteria would be that the relay must not change state for peak acceleration input under a specified g level. Once the acceptance criteria has been cast into a statement which includes the fundamental dynamic response of the structure, the equivalency between various qualification techniques can be described, and the results from different testing methods better interpreted.

Ibanez, et al[7] reported one of the earliest comparisons of test time histories in terms of the peak spectral response amplification over the peak excitation. This comparison is based strictly on the excitation with no regard to how the frequency content matches with the excited structure, and no regard to failure mechanisms present.

Kana[86] has provided another type of relationship between acceptance criteria and the fundamental dynamic properties of a structure. His definition of a damage severity factor (DSF) is based upon the peak and RMS acceleration caused by a specific seismic event. However, the relationship of this criteria with various forms of failure mechanisms remains yet uncertain.

5.1.4 Nonlinearities

The matter of high frequency acceleration (i.e., > 33 Hz) responses induced by rattling nonlinearities has already been mentioned. Recent unpublished research is showing that such responses are very real in their effect on internal electrical and electronic devices mounted in cabinets with loose doors and panels. So long as the devices are tested in an assembly with the entire cabinet, the devices experience a realistic environment. However, if the cabinet is tested first with only dummy devices installed and response measurements are obtained to form the excitation for subsequent device tests, then a real problem develops as to how to best simulate and describe the measured high frequency environment. Operational loads, such as closing of large circuit breakers, can also induce such nonlinear effects on internal components and devices.

5.1.5 Test Sequence

Test sequences typically include five OBE level tests followed by one SSE level. For those cases where independent biaxial testing is involved, this sequence must be applied along each of two different 90° orientations (i.e., front to rear and side to side). Often, five OBE's and one SSE are applied in one direction, the equipment is turned on the simulator, and then a similar test sequence is applied. Other specifications require that five OBE's, turn, five OBE's, one SSE, turn, and one SSE be used as a sequence. The latter obviously requires more time and expense. The process is even doubled for dependent biaxial testing. Uncertainty exists as to which is the correct approach. Unrealistic fatigue damage may be incurred by those tests which require the most repeated runs. However, if a failure does not occur for the more conservative test, then no problem exists.

Another uncertainty exists for the use of actual field items as a test specimen. Once all testing is complete to end of life condition (which may even include some modification after failure and retest), the item is sometimes shipped into the field for installation. The degree of subsequent refurbishment to assure a complete service life is uncertain, and no restrictions are known to exist for this practice.

5.1.6 Methods For Dynamic Load Combination

Recent trends have included the possibility of earthquake and SRV events occurring simultaneously. Vibration transients induced into equipment located on the various floors of a building are rather short duration (2-5 second) events which include higher frequency content (20-150 Hz), as compared with earthquakes. Of course, one must consider how to develop a test which includes both events simultaneously. The use of independent time histories phased and added vectorially seems obvious. However, it is desirable to be able to use less expensive and cumbersome spectral methods. Addition of response spectra directly has no theoretical basis. Therefore, use of some other technique appears necessary. NUREG/CR-2087 "Load Combination Methodology Development", which reports on a probabilistic methodology for developing consistent criteria, suggests that seismic plus SRV will have a low probability. Future work will be addressing appropriate service level for particular load combinations and proper procedures for combining dynamic responses. As a result, the need to combine seismic and SRV laods may not occur.

5.1.7 Fragility

There appear to be few commonly-accepted procedures identified for fragility measurement in equipment today. The concept is defined as an optional form of test in IEEE 344-1975, and some general procedures are discussed. However, very few other published references directly applicable to nuclear plant equipment are available on the subject. The lack of development suffers from the same problems present in the comparison of severities between various tests, i.e., the establishment of relationships between failure and dynamic response. This lack of development probably is one of the reasons why proof testing, rather than fragility testing, is currently far more prominent in qualification of equipment programs. As an option it is not always appropriate to perform a fragility test. However, it is most useful for understanding the failure mechanism of or bounding limits of qualification of a component.

Although the physical design of electrical and electronic hardware used in nuclear plants is considerably different from that used in aerospace hardware, the concepts of fragility applied to both may be considered essentially similar. Some results of fragility studies for aircraft avionics and other equipment are given in References [227-229, 231, 353, 354]. The concepts have been further applied directly to nuclear plant equipment by Kennedy, et al[355]. This latter report is the most comprehensive, and is apparently the only available review document which concerns fragility measurement in nuclear plant equipment. A common measure of fragility for any type of equipment is defined in terms of a probability measure, as shown in Figure 5.1-6. This simplified representation shows a frequency of failure as a function of an amplitude parameter (acceleration in this case). It is emphasized that such curves can only be developed in a statistical sense. Various data necessary for defining fragility for typical nuclear plant equipment is given in Table 4-2 of Reference [355]. Typical failure modes, sensitivity parameters, and other information is also listed. For convenience, this table is reproduced in the Appendix, Section 9.0.

5.2 Qualification by Analysis

The state of the art for seismic qualification of equipment by analysis has been covered in considerable detail by Kennedy, et al in Reference [087]. That review is still very much applicable at the present date. Therefore, herein we will make only a few additional comments on analysis methodology.

Seismic qualification of equipment by analysis includes one or more of the following methods:

1. Static method
2. Response spectrum
3. Time history (modal analysis)
4. Time history (direct integration)

The selection of a suitable method to qualify specific equipment depends on many factors. Among the factors considered in the selection of an

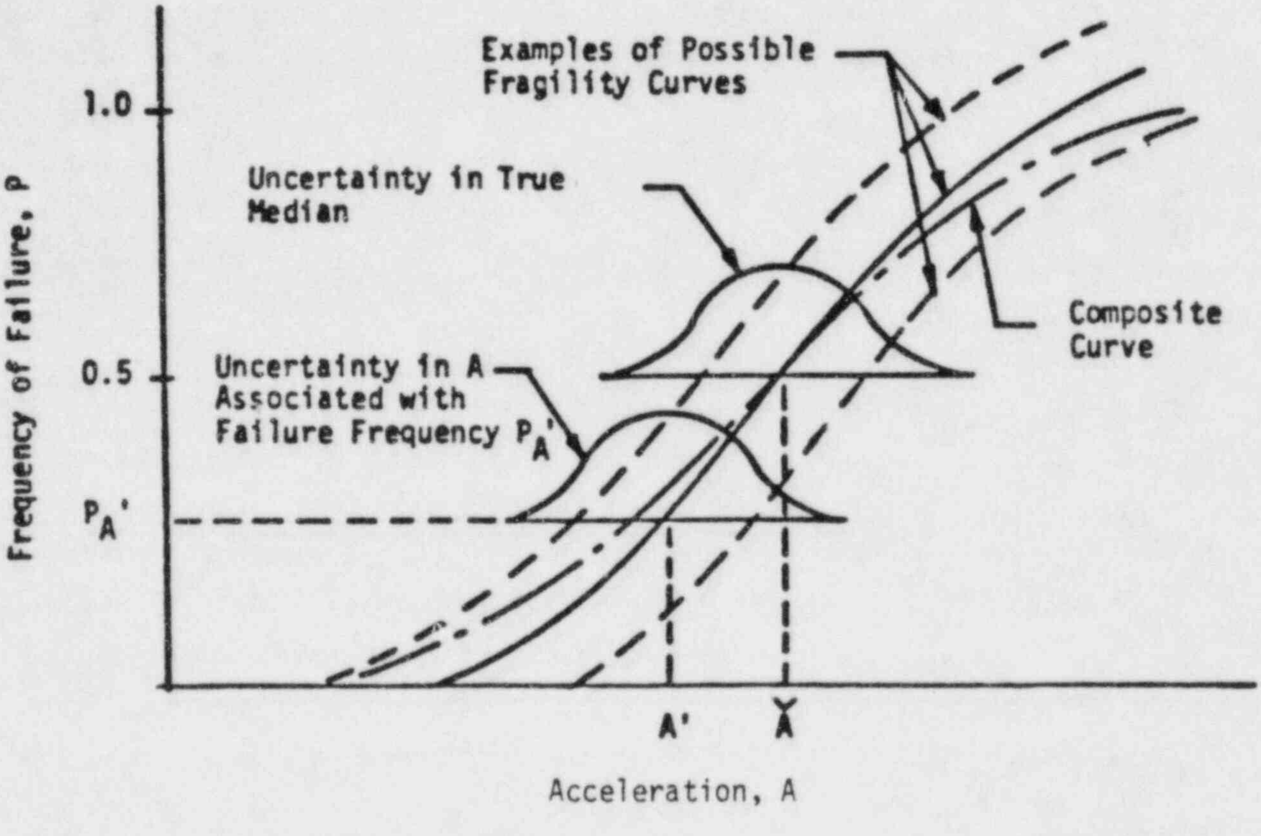

Figure 5.1-6 Simplified Representation of Fragility Curve (Ref. 355)

analysis method are definition of the form of the seismic input, prediction of the dynamic response of the structure, correlation of response with failure mechanisms of the structure, economic resources available, and time available to perform the analysis. Recent examples of dynamic and seismic analysis of a variety of equipment can be obtained from Reference [361].

5.2.1 Degree of Model Complexity

All programs aimed at qualifying equipment by analysis begin with the development of a mathematical model, regardless of the solution method. The mathematical model, which includes synthesis of a complex structure into an aggregate of beams, plates, or shells, should be sufficiently accurate to allow prediction of the essential dynamic behavior. Such synthesis of a physical structure into an analytical representation is both an art and science. The art involves knowing how much detail to incorporate into the model to yield conservative results, yet discarding unnecessary details which overly complicate the problem. The science involves the proper application of physical and mathematical principles to form a consistent set of equations whose solution is valid. Thus, modelling a given physical structure is also a creative art. If two groups of qualified engineers model a structure the result may very well be two different mathematical models. However, both would predict similar dynamic results if they are valid models. Hence, some uncertainty may always exist on the exact adequacy of a model. Furthermore, typically the models are linear mathematically, unless some known nonlinear mechanism can be included. Mechanisms of the rattling type described in Section 5.1.4 have not been evaluated in the past, and their effects can cause significant errors if cabinets are qualified analytically.

After the mathematical model of the structure has been synthesized the model must be loaded to obtain a response prediction. For structures not classified as Category 1, or whose failure would not affect Category 1 equipment, often equivalent static forces are used for the loading. The equivalent static loads are usually calculated using the peak value of the required response spectrum for justifiable damping values and localized mass values. As directed by IEEE 344-1975, this force value has been increased by 50% in the past to account for uncertainties. However, justification of the use of this value is now being required.

For Class 1 and other selected structures, loading of the mathematical model is usually accomplished by one of two representations of the earthquake: typically a response spectrum, or time history. However, a trend is now growing for the use of stationary random vibration techniques (power spectral density) to represent an earthquake as well. In fact, by means of the transformations developed by Unruh and Kana[202], it is now possible to generate flow response spectra from ground response spectra, without the intermediate development of a time history.

5.2.2 Synthesis of Damping

Whether loaded by equivalent static forces or dynamic motion representing an earthquake, analytical models include a mechanism of energy dissipation. NRC R.G. 1.61 provides the recommended damping values listed in Table 5.2-1. These values depend on whether the earthquake acting on the structure is an OBE or SSE, and are based on average measured data. Additional typical damping values are listed in Table 5.2-2. The results in these two tables can be contrasted to typical damping values presented by Newmark[322] and given in Table 5.2-3. Thus, various ranges are available and the analyst is forced to choose from a rather diverse list of values.

Generally when damping is discussed the inferred mechanism is viscous, i.e., the damping force is proportional to velocity. Analysts have long recognized that the use of this damping mechanism is a mathematical convenience rather than a precise description of the energy dissipation mechanism in a structure. This model of damping has persisted for it provides reasonable results that can be economically derived.

Damping values referenced in test reports or analysis are usually single numbers given without reference to any particular mode of vibration. Reference [284] describes two extensively used methods for determining an equivalent modal damping matrix or composite damping matrix to be used when dissimilar materials are present. The two

TABLE 5.2-1 DAMPING VALUES

(Percent of Critical Damping)

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 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

TABLE 5.2-2 SUMMARY OF DAMPING VALUES[284]

Source of Data	Component or Structure	Type of Excitation	Amplitude or Stress Level	Damping (% of Critical)
(a) Nuclear power plant components and structures				
1. San Onofre Nuclear Generating Station Unit (1): Forced vibration tests and responses to Lytle Creek and San Fernando Earthquakes (Pressurized Water Reactor)	Steam Generator	Vibration Generators	1.4 mils	1.5–2.0
		S. Fernando Earthquake	5 mils 0.23g max. (transverse)	3.3
			70 mils 0.18g max. (radial)	3.0
			1.8 mils 0.15g max. (vertical)	0.4
		Lytle Creek Earthquake	0.03g max (transverse)	≃ 5
	Pressurizer	Vibration generators	1.3 mils	0.9, 1.5
		Lytle Creek Earthquake	0.04g and 0.08g max	2 and 9
	Pump	Vibration generators	3.7 mils N-S	1.3
			6.6 mils E-W	0.8
			N-S and E-W	0.4
2. Indian Point No. 1 Primary Loop Vibration Test Program (Pressurized Water Reactor)	Steam Generator	Shaker (Sine beat)	9.5 mils, 10.5 mils (tangential)	3, 2.2
			37 mils (radial)	5
	Crossover Leg		0.3 mils	5
	Pump		1.9 mils, 1.5 mils	0.95, 1.3
3. Laboratory testing of steel pipe and reinforced concrete specimens	Fixed-end pipe	Laboratory shaker (sinusoidal)	7.5 to 108% of yield	0.3 to 14.0
	Simply-supported pipe		27 to 130% of yield	5 to 20
	Fixed and simply-supported pipe		0.3 to 3.0g 1000 to 2300 psi pressure	1.2 to 3.6
	Reinforced concrete		18 to 100% of UCS	1.9 to 8.9

TABLE 5.2-2 Continued

(1)	(2)	(3)	(4)	(5)
Isuruga Nuclear Power Plant piping vibration tests.	6 to 16 in. pipelines	Static displacement	---	3.2 to 3.6 Avg. = 3.4
	0.75 to 2.5 in. pipelines		Low	0.13 to 3.6 Avg. = 1.1 (Non-insul.) and 1.7 (Insulated)
5. Oak Ridge Experimental Gas-Cooled Reactor (EGCR)	Steam generator	Forced vibrations	10 mils E-W	1.3
			5 mils N-S	0.9
	Containment structure (steel shell with concrete wall lining)		2.5 mils @ 4.65 Hz E-W	1.5-2.0
			2.5 mils @ 4.2 Hz N-S	3.0-3.5
			Torsion	2.0
	Steam generator	Static displacement and explosives	Small deflections	0.5-1.5
			Higher deflections	3-7
	Steam line		1.0 in. N-S	2-7
			0.2 in. E-W	3
6. Laboratory Tests on KEP-2-105 CRDM	CRDM and Support System	Static displacement	0.125 to 0.375 in.	3.5 to 17.5 Avg. = 8
7. Carolinas–Virginia tube reactor tests	Concrete containment with internals and components	Vibration generator	Various	5 to 10
(b) Non-nuclear type concrete and steel structures				
8. Tests on Las Vegas buildings	Reinforced concrete highrise buildings	Nuclear explosion induced ground motion	0.009 g to 0.052 g	1.0 to 11.0 average = 5.6
9. 4-story test structures, AEC Nevada test site	Reinforced concrete frames with partitions	Static displacement and vibration generator	0.001 to 0.200 cm.	0.8 to 5.0, average = 2.4
	Reinforced concrete frames w/o partitions		0.004 to 0.06 cm	0.6 to 2.4, average = 1.1

TABLE 5.2-2 Continued

Source of Data (1)	Component or Structure (2)	Type of Excitation (3)	Amplitude or Stress Level (4)	Damping (% of Critical) (5)
10. Various school and apartment type buildings	Reinforced concrete buildings with concrete shear walls, floors, partitions	Vibration generator	0.0001 g to 0.0008 g	Lowest average for any building = 1.3, highest value = 12.4
11. Tests of Small Concrete Beams	Prestressed concrete beams	Steady-state and free vibrations	3 to 11 mils steady-state amplitude	0.54 to 2.50, average = 1.15
			30 to 730 mils free deflection	2.0 to 6.6, average = 4.3
12. Intake Tower, Encino Dam, Calif.,	Round, reinforced concrete water intake tower	Vibration generator	Max. at top = 0.043g	2.0, 2.6 and 2.8
Fernbridge Chimney	Circular reinforced concrete chimney	Rocket firing	0.56 in. max.	0.8 and 1.0
13. Univ. of Calif. Medical Center, East Bldg.; Tokyo Kaijo Bldg.; Central Engineering, C.I.T. Campus Bldg.	Steel frame buildings with concrete floor slabs	Vibration generator	---	0.4 to 13; 3 to 5; 0.4 to 3.6
14. Chimes Tower Structure, New York World's Fair; Talcahuano Steel Plant Stacks	Steel tower structure	Vibration generator	750 mils	2 to 3 (first mode)
				5 to 6 (second mode)
	Steel stacks with gunite lining	Static displacement	Small	3 to 4

Note: 1 in. = 25.4mm; 1 psi = 6.9 kPa

TABLE 5.2-3 TYPICAL VALUES OF DAMPING IN NUCLEAR REACTOR FACILITIES [322]

Stress level	Type and condition of structure	% of critical damping
1. Low, well below proportional limit, stresses below 1/4 yield point.	Vital piping	0.5
	Steel, reinforced or prestressed concrete, wood; no cracking; no joint slip	0.5-1.0
2. Working stress, no more than about 1/2 yield point.	Vital piping	0.5-1.0
	Welded steel, prestressed concrete, well reinforced concrete (only slight cracking)	2
	Reinforced concrete with considerable cracking	3-5
	Bolted and/or riveted steel, wood structures with nailed or bolted joints	5-7
3. At or just below yield point.	Vital piping	2
	Welded steel, prestressed concrete (without complete loss in prestress)	5
	Reinforced concrete and prestressed concrete	7-10
	Bolted and/or riveted steel, wood structures with bolted joints	10-15
	Wood structures with nailed joints	15-20
4. Beyond yield point, with permanent strain greater than yield point limit strain.	Piping	5
	Welded steel	7-10
	Reinforced concrete and prestressed concrete	10-15
	Bolted and/or riveted steel, and wood structures	20
5. All ranges; rocking of entire structure*	On rock, $\nu_s > 1800$ m/sec	2-5
	On firm soil, $\nu_s \geq 600$ m/sec	5-7
	On soft soil, $\nu_s < 600$ m/sec	7-10

[*] Higher damping ratios for lower values of shear-wave velocity ν_s.

methods are based on proportioning the damping factors according to the mass or the stiffness of each element. The formulations for proportioning are:

$$\bar{\beta}_j = \frac{\{\phi_j\}^T[\bar{M}]\{\phi_j\}}{\{\phi_j\}^T[M]\{\phi_j\}}$$

and

$$\bar{\beta}_j = \frac{\{\phi_j\}^T[\bar{K}]\{\phi_j\}}{\{\phi_j\}^T[K]\{\phi_j\}}$$

where

$\bar{\beta}_j$ is the equivalent modal damping of the j^{th} mode

$\{\phi_j\}$ is the shape vector of the j^{th} mode

$[\bar{M}] = \sum_{n=1}^{N} \beta_n [M_n]$ is the modified mass matrix constructed from the product of the modal damping ratio and the mass matrix

$[\bar{K}] = \sum_{n=1}^{N} \beta_n [K_n]$ is the modified stiffness matrix constructed from the product of the modal damping ratio and the stiffness matrix.

This approach to synthesis of damping for composite structures has never been validated experimentally. Kana and Unruh[336] have offered an alternate approach which has been validated in aerospace type structures.

In summary, damping is an experimentally derived quantity whose value is usually conservative as a result of low level testing. Analysts in the papers reviewed tend to use damping as a precise number without evaluating the sensitivity of the structural response result to a range of damping. However, recent analytical studies are being performed in the Seismic Safety Margin Review Program to evaluate the sensitivity of structural response to the damping value in order to bound the fundamental input parameters. Qualification of components to high level excitation should use damping values associated with that level of input.

5.2.3 Acceptance Criteria

Acceptance criteria used in conjunction with analytical qualification of equipment are usually based on material strength properties or a change in a critical dimension. Often acceptance criteria are not clearly stated in the reports reviewed or insufficient detail is provided to permit the reader to evaluate the physical significance of the acceptance criteria used in analytical equipment qualification programs. The most important deficiency in the use of analytical qualification lies in the difficulty of including a mathematical description of functionality. In effect this is a deficiency similar to the lack of relationships between failure mechanisms and dynamic response parameters, as described in Section 5.1.3. Thus, for better use of analytical models in qualification, more specific relationships between failure in functional response and dynamic responses need to be derived.

5.2.4 Methods of Mode Combination

Coats, et al[273] have shown that SRSS of modal responses of structures may not be conservative in certain cases. More specifically, algebraic summation of higher modal responses is appropriate where base shear is significant.

5.3 Combined Experimental and Analytical Qualifications

Some of the equipment used in a nuclear power plant exceeds the testing capabilities of even the largest seismic simulator. Furthermore, existing equipment in operating plants cannot be removed for simulator testing without incurring costly plant shutdowns. Therefore, to qualify equipment under these conditions, IEEE 344-1975 describes qualification by combining analysis and testing. This standard allows a choice of several different methods of excitation to determine the dynamic properties of the equipment including frequency, damping, mode shapes, and transfer functions, and modal masses. These data are used in subsequent analysis to either 1) validate and refine or 2) define an analytical model. The amount of data taken and its accuracy are significantly more important for the latter approach.

5.3.1 Validation and Refinement of Analytical Models

In this approach, an analytical model of the structure in question is developed from drawings and design information. The equipment may not in fact even exist yet at this stage. The model usually consists of some finite element representation, similar to that equipment which is qualified purely by analysis. However, when the actual equipment becomes available (or if it is already available in an operating plant), then experiments are conducted on the equipment to determine its modal properties. For this the equipment is fixed-base mounted either in a simulated or actual inplant condition. Sufficient modal data are measured to verify natural frequencies and mode shapes, and damping is measured for each mode by a suitable method. Mass and/or stiffness properties of the analytical model are subsequently refined if necessary, to allow complete agreement with the experimental data throughout the range of interest. Then, the validated analytical model can be used to predict stress and motion responses to earthquake motion excitation of the base of the structure by any of the previously-mentioned analytical methods. This approach has an enormously greater advantage over purely analytical qualification, since variations in boundary conditions and other inplant peculiarities can be determined more readily. Examples of this procedure have been given by Ibanez, et al[278, 366] for various nuclear plant equipment.

5.3.2 In Situ Testing

This terminology refers to a special type of combined test and analysis methodology which is applied principally to equipment in existing operating plants. However, it can be applied to any equipment that already exists and can be mounted in either simulated or actual operating conditions. It has only recently been developed for seismic qualification but is gaining interest rapidly. The complete process involves measurement of equipment dynamic characteristics (transfer functions) at various (usually many) significant locations on installed equipment, and subsequent use of these data to develop an analytical model of the structure, and then predict its response to seismic excitation. The method is useful to predict motion response at elevated positions on the equipment to form inputs for device tests, as well as to be able to predict the ability of the entire assembly to withstand seismic stresses and function properly. However, there are uncertainties present in several areas of this methodology.

The first step for In Situ testing involves development of a fixed-base analytical model from transfer function measurements. Techniques for such measurements may include slow or rapidly swept sine, broad band random, or transient excitation. However, significant differences in results can be obtained from the same hardware specimen, depending on the exact technique used, unless considerable care is exercised. Details of these anomalies are described in References [356-358]. Differences which result from the different techniques are usually aggravated in specimens with light damping (i.e., <2%), which includes many types of equipment used in nuclear plants. Use of random and transient techniques require dedicated modal analysis computers, and significant experience in their use. The result of this part of the study is a listing of all natural frequencies, normal mode vectors, modal damping and modal mass for the frequency range investigated. As with any analytical model development, determination of a sufficient number of nodal points for accurate description of the equipment is a matter of considerable experience and judgement. Furthermore, no matter how the subsequent analytical model is formulated, its definition is based on the initially-measured experimental data. Therefore, the only sure way of checking for errors appears to be to measure the initial transfer functions under more than one set of conditions to establish some certainty in their validity.

The second step in the process involves a development of the physical mass matrix for the model. This is necessary for use in modal participation factors of a moving base system. This step involves solution of an N-dimensional set of algebraic equations for N-nodal points. The set of equations is based directly on transfer function and modal mass data. Uncertainties in the latter approach result from measurement errors, nonlinearities, and nonproportional damping. Some preliminary data on the application of this method to equipment in the Knosheng Power Plant has been given by Gorman[359]. Finally, the third step in the process involves the use of the analytical model for prediction of response to seismic base motion, as with any of the previously-described analytical model techniques.

5.4 Synergistic Effects and Aging

5.4.1 Test Sequence

Synergistic effects are a topic receiving considerable attention, although this is only a recent development in the nuclear industry. IEEE 323-1974 lists the type tests and suggests the order for performing these type tests for equipment qualification. For most equipment and applications the following constitutes the most severe sequence:

1. Inspection
2. Normal operation
3. Extreme operation
4. Aged (time and radiation)
5. Mechanical vibration
6. Seismic qualification and operation
7. Operation during exposure as appropriate
8. Post-accident exposure and operation
9. Inspection and possible disassembly.

However, this standard notes that only a few equipment qualification programs have verified that the above specified sequence is the most severe. The apparent lack of emphasis on sequence justification may be the result of few investigations having been conducted to identify synergistic effects or the current questionable methods of component aging. The presently available NUREG 0588 emphasizes the need to consider synergistic effects. This emphasis appears to result from limited tests by Sandia Corporation, whereby synergistic effects are being evaluated.

5.4.2 Aging Methods

Aging is a major test requirement included in component qualification. The draft of NUREG 0588 specifies that Cobalt 60 is an acceptable radiation aging source and the Method of Arrhenius is an acceptable method to simulate degradation due to thermal aging.

However, it must be recognized that there is currently no deterministic method of extrapolating the effects of aging processes produced in the laboratory in 3 to 6 months (or other short periods of time), to the overall aging effect on a component after 40 years of service life + 1 year post accident (44 years with 10% margin). A relevant statement from a recent thorough review[324] of equipment aging theory and technology states:

> "The dominant picture that results from the study is that there is no comprehensive scientifically rigorous solution to the problem of accelerating the aging of equipment. Aging that can be accelerated in ways that yield verifiable correlation between real and simulated aging is an exception rather than the rule."

Furthermore, this report concludes that "major advances and equipment aging technology are not expected within the foreseeable future". A number of methods of thermal aging have been used and are currently in use. These methods include thermogravitational analysis, simple rules of thumb, (e.g., the so-called 10°C rule) and Arrhenius extrapolations. At this time, no available technical data provide evidence of the superiority of any particular aging method. Techniques which involve chemical analysis may yield more data for identifying materials which are potentially ageable in a component, but, the data are misleading when inappropriately applied.

5.4.3 Arrhenius Model

A number of models for aging have been proposed and used including the Arrhenius model, the Eyring model, the Inverse Power model, and the 10°C Rule. These models are discussed in detail in Reference [324]. Of these models, the most widely used is the Arrhenius model. This model relates the reaction rate of a single chemical reaction to temperature and a characteristic activation energy constant of the single reaction. The equation is given as

$$R = -ae^{-E/KT}.$$

where

R is the reaction rate

E is the activation energy

K is Boltzmann constant

T is the absolute temperature.

This equation shows that as temperature increases, the reaction rate increases. For a constant temperature, reactions with a larger activation energy constant have slower reaction rates than those for a smaller. It is postulated that the materials of a component will experience accelerated aging if the reactions within the materials, which would have occurred over the qualified life of the component, are increased by baking the components at elevated temperatures (thermal aging at the temperature, T_A). To obtain the acceleration factor for aging resulting from baking the items at elevated temperatures, the reaction rate at the aging temperature is ratioed to the reaction rate at the service life temperature to obtain a reaction rate ratio

$$R_R = \exp \frac{E}{K} \left(\frac{1}{T_S} - \frac{1}{T_A}\right)$$

Since it is postulated that the time of aging is inversely proportional to the reaction rate, R_R is equal to t_s/t_a and

$$\frac{t_s}{t_a} = \exp \frac{E}{K} \left(\frac{1}{T_S} - \frac{1}{T_A}\right)$$

where

t_s is the service time

t_a is the aging time.

Assuming T_s to be constant at 44 years, this model predicts shorter aging times for reactions with larger activation energy constants for given aging and service life temperatures. Since the reality of thermal aging is that service life temperatures are specified, and that the aging temperature chosen is usually the maximum which a component can withstand without creating thermal related failures (i.e., a failure related only to exceeding some maximum temperature to which the component is susceptible, not due to an aging mechanism), it is obvious that the maximum aging time according to this model can be obtained only by finding the minimum pertinent activation energy constant to substitute into the model.

A discussion of the mathematical justification of the Arrhenius model through kinetic theory is given in Reference [235]. Some of the assumptions behind this derivation are as follows:

1. A single chemical reaction is involved.
2. The mechanical or electrical properties of a material are dependent upon the decomposition or production of chemical substances resulting from this single chemical reaction.
3. The reaction is endothermic (requiring energy from external sources for its completion).
4. The reactants are homogeneously mixed and free to interact randomly.
5. There are sufficient reactants available such that the reaction is continuous with time.

In applying the Arrhenius equation as a model for the aging of typical materials used in Class 1E nuclear components, the following additional assumptions are made.

1. The aging of materials in the component is thermally related.
2. Given that a common failure mode analysis indicates several potential failure modes of a component as a result of the potential effects of aging on several materials in the component, it is generally assumed that the material with the lowest activation energy constant in the component would contribute to a failure mode which represents the weakest link in the chain of potential failure mode. In other words, aging failure of the component is correlated to the minimum activation energy constant of the materials but otherwise uncorrelated to the probability of occurrence of various potential failure modes.

Examination of these assumptions reveals how poorly the Arrhenius model applies to the thermal aging of Class 1E components for nuclear applications. The assumption that a single chemical reaction governs the aging process of a material is less likely than one in which multiple chemical reactions are occurring within a given material. Certainly many reactions are occurring within the many different materials of which a typical component is comprised. Each of these reactions would have an activation energy constant, in general, different from any of the others. Different chemical reactions are dominant in a material, depending on the temperature the material is experiencing. An activation energy constant determined from measurements made on a material at high temperatures, will not necessarily give the same results as determining an activation energy constant at lower temperatures. For this reason activation energy constants obtained from thermogravitational analysis may give misleading results even for a homogeneous material when applied to aging at typical service life temperatures. Complex reactions, with more than one type of degradation product formed from the original material, and simultaneous consecutive reactions, in which the degradation products in turn degrade, lead to nonlinear Arrhenius plots for which an activation energy "constant" is inapplicable[329].

Since it is the effect of aging on the functionality of a component that is of primary importance in nuclear qualifications work, and not the results of chemical analysis, it needs to be stressed that not all potentially ageable material in a component are of equal importance to its likelihood of failure. There may be a number of active failure modes which independently can be an Arrhenius model but simultaneously cannot. Indeed, a component failure mode analysis must be made to determine what, if any, materials in a component which are ageable, may even contribute to potential component failure. Furthermore, of the materials which may contribute to component failure, the assumption that each of these failure modes are equally likely, or would have equal effect on the component functionality in terms of its Class 1 essential performance requirements is unsupported. For example, a relay may fail because the coil wiring insulation shorts out or because of plastic deformation of the armature under tensile stress. In applying the Arrhenius model to component, it may be determined that the activation energy associated with tensile strength in the armature material is less than the activation energy associated with bulk resistivity of the coil insulation. On the other hand, failure of the coil insulation would be complete once the bulk resistivity became less than some value due to aging. Failure of the armature may or may not occur for a whole range of values for which the tensile strength of the material is exceeded. For this reason, it may be more probable that the relay would fail due to failure of the coil insulation than due to failure of the armature even though the activation energy associated with this failure mode is greater. In general however, in applying the Arrhenius model, the lowest activation energy constant for any material is assumed to determine the time temperature relationship for aging of the overall component since all failure modes are considered equally probable.

In view of the above discussion, the methodology of age testing is obviously in a very preliminary state of development. Significantly more work will be necessary before more confidence can be attributed to results obtained. However, in the meantime it is the most practical methodology available.

6.0 EQUIPMENT SUBGROUP ANOMALIES

After a careful review of the information presented in Section 4.0, it is possible to conclude that several anomalies exist with regard to equipment subgroup qualifcation procedures. The most significant of those anomalies are summarized in this section.

6.1 Fragility Data for Most Equipment

There is little fragility data or methodology from the open literature. This is probably caused by a lack of emphasis on fragility as codes and standards allow the use of either fragility or proof testing. A hard look at the concept of fragility is appropriate to determine its usefulness to qualification methodology. A component can be qualified to meet its specified service conditions without the need to determine its fragility.

6.2 Aging Data for Most Equipment

It appears that most of the equipment qualified prior to 1975 has been subject to very little, if any, age testing. However, there are operating nuclear power plants, fossil-fired power plants and industrial plants with components naturally aged under mild and harsh temperature, humidity vibration and dust conditions. This data should be evaluated for usefulness to aging methodology.

6.3 Liquid Vessels and Submerged Structures

This type of equipment has generally been qualified by analysis. However, earlier systems have been qualified by the Housner method, which includes the assumption of a rigid vessel and only horizontal motion. More recent work has demonstrated that vessel flexibility and vertical motion can both have a significant effect on the design results. Likewise, early design of submerged structures includes simply the addition of approximations for added mass of the liquid in which a structure is vibrating. More accurate expressions for both added mass and damping are now available. Qualification for any such systems should include consideration of fluid/structural interaction to an appropriate degree.

6.4 Large and Small Piping

Piping systems are generally qualified by analysis and fall within a group of large structures that are subject to excitation at multiple attach points [360, 3[illegible]2]. Because of the overall size of a given pipe system, excitation at remote locations can be only partially correlated with that at other locations. The response spectrum method does not allow for any degree of correlation for multiple inputs, i.e., the assumption is that all inputs are essentially statistically independent. As a result, SRSS techniques are applied for prediction of responses. However, for correlated multiple inputs, such assumptions are not valid in general, and other techniques must be sought. For such a case the use of power spectral density and cross-spectral densities for the excitation appears to provide a plausible approach to the problem. The agreement would be applicable to a similar problem for any large scale structure.

7.0 RECOMMENDED RESEARCH FOR ALLEVIATION OF ANOMALIES

The previous two sections have identified a variety of anomalies associated with nuclear equipment qualification procedures. It is recognized that some are of significance, while others may turn out to be insignificant in their potential impact on the qualification process. Therefore, in this section a specific listing of recommended research is given for attention to those problems that are considered the most important. The discussion is given in two parts, the first of which includes work currently in progress at SwRI; the second recommends work not previously included in the SwRI program.

7.1 Work Currently in Progress

7.1.1 Fundamental Criteria for Earthquake Simulation

The recognized intent of earthquake simulation at the ground level is to produce a motion which is characteristic of the strong motion portion of an earthquake. This may be done by developing a motion whose frequency content, stationarity, probability density, and other characteristics are similar to those of that for a number of sample earthquakes. Typical floor level simulations can then be based on the developed ground level simulations after being transmitted through linear filters (structural floor levels). Thus, quantitative criteria for motion simulation will result. This will indicate what if any response spectrum tolerance specification should be recommended, or whether other additional parameters should be included in the specification.

7.1.2 Response Spectrum vs. Power Spectrum Transformation

Although the basics of this transformation have already been developed, further work will be done to complete confidence in the method. Its use is very important for qualification by both test and analysis.

7.1.3 Combined Analysis and Test Methods

It is always desirable to synthesize a physical structure with the simplest model possible. However, the optimum level varies considerably from one type of equipment to another. Some light will be shed on this process by comparison of predicted seismic responses with those measured for a typical local panel. At the same time the same specimen will be set up as in an in-situ condition, and its dynamic characteristics will be measured by a variety of excitation techniques. The degree of complexity and amount of data necessary for a valid in-situ development of an analytical model will be determined. The effects of boundary condition variation, data processing techniques, and other uncertainties on the results will be included.

7.1.4 Combination of Environments

Methods of specifying combinations of environments will be developed. This will be based on seismic, SRV, and seismic + SRV simulations.

7.1.5 Multiple Axis Excitation

The question of adequacy of less than three dimensions to simulate a three dimensional excitation is ever present. Information will be developed by an analytical study of the local panel specimen. Responses will be predicted and compared for two and three axis simulations. It is recognized that other programs are also currently in progress to provide a more complete study of this problem.

7.1.6 Comparison of Test Methodologies

Development of a systematic method of comparing the adequacy of pre-1975 tests with those conducted therafter is of extreme importance. At present, solution to this problem is only in its infancy. At first glance, it appears that this problem is related to a measure and prediction of fragility, in some ways. In any event, solution of the problem for the great variety of equipment that has been identified will be an extremely difficult task. It appears that obtaining the exact form of tests that have been used for specific subgroups of equipment will be a task that can be accomplished only over some considerable period of time. Rather, it appears feasible within the present program time and effort to catalogue the typical forms or methodologies that have been used and are being used for testing (i.e., Table 3.3-2), and compare the potential consequences of the application of certain types of tests to each appropriate equipment subgroup. Realistically, it is felt that only a start on the solution to this problem will be accomplished under the present program. In view of the urgency of the problem, it is recommended that the present efforts be expanded, or parallel efforts be conducted simultaneously.

7.1.7 Fragility Concepts

The present review indicates that insufficient data is available to infer fragility information from previously available data (this conclusion is based on data available in the open market). Some fragility data is probably available from company proprietary files, if a means of gathering this information were developed. However, it appears that changes in regulations to provide such data for future qualifications is the only feasible means of developing a set of data with any confidence in its validity. Furthermore, fundamental work on the basic concepts of fragility and its measurement should be pursued. This work should be encouraged to include development of entirely new parameters for quantification of fragility, if appropriate. The present SwRI effort will not provide a final solution to this problem.

7.1.8 Line Mounted Items

Analytical and experimental efforts are being conducted to determine the adequacy of RIM tests for line mounted items. In this case it is suspected that present tests are significantly more conservative than is necessary. Replacement of sine beat tests with a swept narrow band random test may prove feasible.

7.2 Other Recommended Activities

There is a present realization that seismic qualification of a piece of equipment can readily be nullified by improper plant installation, or even by improper maintenance programs, years after initial installation. A program should immediately be initiated to study the extent of this problem, and its impact on the qualification status. This should include ultimate recommendations for tracking equipment and logging work that has been performed on it.

The previously identified problem of questionable design for fluid containers to withstand fluid/structure interaction deserves further consideration. A program should be conducted to survey the various kinds of containers used in nuclear plants, and exact procedures used in their qualification. Then, revised procedures which allow for a measure of fluid/structure interaction appropriate for their specific use should be recommended. Similar efforts should be applied to that equipment which must operate in submerged environments.

Programs which deal with other than seismic environmental aging and synergistic effects are very much in order. It is important first to categorize which equipment is important for what environments, and then a development of appropriate forms of tests and test sequences.

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SECTION 9.0

APPENDIX

TABLE 9.0-1 CLASSIFICATION OF SUBSYSTEMS FOR SEISMIC QUALIFICATION AND RESPONSE CHARACTERISTICS

(From Ref. 087)

Item No.	GENERIC COMPONENT OR SUBSYSTEM	LOCATION IN PLANT	FUNCTION (1) OF EQUIPMENT	GOVERNING (2) CODE OR STANDARD	QUALIFICATION METHOD	SIZE/SHAPE OF EQUIPMENT	RESPONSE (3) CHARACTERISTICS	COMMENTS
1	RCS Vessels	Containment Bldg.	Coolant Boundary (Passive)	ASME Sect. III	Analysis	Large. Vertical. Slender Heavy wall	Med. Freq.	Predominant modes from beam bending and support deffection. Beam Modes commonly used.
2	Reactor Core Support Structure	Reactor Vessel	Support Fuel + Control rods	NSSS Criteria ASME Sect. III	Analysis	Large. Plate & Shell Structure	Med. Freq.	Complex plate and shell structures requiring complex dynamics models.
3	Fuel Rod Cluster	Reactor Core	Contain fuel pellets and fission products (Passive)	NSSS designated design criteria	Analysis	Long. Slender	Med. Freq.	Several fuel rods in each cluster supported at intervals by grid assemblies. Beam bending modes are predominant. Non liner response of rods in grids.
4	Control Rods and Drives	Reactor Core	Reactivity Control (Active)	ASME Sect. III for Pressure housings, NSSS criteria for functional mechanisms.	Analysis	Long. Slender	Med. Freq.	Predominant mode is beam bending.
5	Large Dia. Pipe 3" & Greater	Misc. Locations	Coolant Boundary (Passive)	ANSI B31.1 ASME Section III	Analysis	Continuous 3 D Beam	Med. Freq.	All wall thickness from Sch 40 - 120
6	Small Dia. Pipe, 3"	Misc. Locations	Coolant Boundary (Passive)	ANSI B31.1 ASME Section III	Analysis	Continuous 3 D Beam	Med Freq.	All Wall thicknesses Sch. 40 - 120

TABLE 9.0-1 - Continued

Item No.	GENERIC COMPONENT OR SUBSYSTEM	LOCATION IN PLANT	FUNCTION (1) OF EQUIPMENT	GOVERNING (2) CODE OR STANDARD	QUALIFICATION METHOD	SIZE/SHAPE OF EQUIPMENT	RESPONSE (3) CHARACTERISTICS	COMMENTS
7	Large Vertical Vessels with Formed heads	Containment & Aux. Bldg.	Coolant Boundary (Passive)	ASME Sect. VIII ASME Section III	Analysis	Vertical Cylinder, Thin wall	Low Freq.- Med. Freq.	Fluid sloshing and wall flexibility to be considered in analysis.
8	Large Vertical Flat Bottom Vessels	Outside	Coolant Boundary (Passive)	ASME Sect. VIII ASME Sect. III	Analysis	Vertical, Cylindrical, flat bottom, thin wall	Low Freq.- Med. Freq.	Fluid Sloshing and wall flexibility to be Considered in Analysis
9	Large horizontal Vessels	Misc. Locations	Coolant Boundary (Passive)	ASME Sect. VIII ASME Section III	Analysis	Horizontal Cylinder, Thin Wall	Low Freq.- Med. Freq.	Fluid sloshing and wall flexibility to be considered in analysis.
10	Small Vessels	Misc. Locations	Coolant Boundary (Passive)	ASME Sect. VIII ASME Section III	Analysis	Horz. or Vert. Cyl. or Sphere	Low - High Freq.	Fluid sloshing to be considered. Tank wall assumed rigid. Supports may be flexible or rigid
11	Buried Pipe	Misc. Locations	Coolant Boundaries (Passive)	ANSI B31.1 ASME Section III	Analysis	Continuous 3 D Beam	Pipe strain follows soil strain.	Empirical static analysis.

TABLE 9.0-1 - Continued

Item No.	GENERIC COMPONENT OR SUBSYSTEMS	LOCATION IN PLANT	FUNCTION (1) OF EQUIPMENT	GOVERNING (2) CODE OR STANDARD	QUALIFICATION METHOD	SIZE/SHAPE OF EQUIPMENT	RESPONSE (3) CHARACTERISTICS	COMMENTS
12	Large Vertical Centrifugal Pumps	Containment Bldg. and Intake Structure	Pump Reactor and Condensor Coolant (Active)	NSSS & AE Specified Criteria ASME Sect. III for Pressure Boundary, IEEE 344 for Elect. Motor	Analysis	Tall, Vertical, Cylindrical	Med. Freq.	Elect Motor or Turbine Driven.
13	Med. to Large Horizontal Pumps and Compressors	Misc. Locations	Pump Coolant (Active)	NSSS & AE Specified Criteria ASME Sect. III for Pressure Boundary, IEEE 344 for Elect. Motor	Analysis	Compact, Heavy	Med.-High Freq.	Elect Motor, Turbine or Diesel driven.
14	Small Pumps <8"	Misc. Locations	Pump Coolant (Active)	NSSS & AE Specified Criteria ASME Sect. III for Body. IEEE 344 for Elect. Motor	Analysis	Compact, Rigid	High Freq.	Reciprocating and centrifugal Turbine, Elect. Motor Drive.
15	Large Motor Operated Valves	Misc. Locations	Coolant Flow Isolation & Control (Active)	ANSI B16.9 ASME Sect. III for Body. IEEE 344 for Operator	Analysis of Valve, Test of Operator.	Rigid Body with Extended Operator	Med. - High Freq.	Isolation & Butterfly Valves. Simple Dynamic Models to calculate operator response.
16	Large Relief & Check Valves	Misc. Locations	Pressure Relief, Flow direction Control (Active)	ANSI B16.9 ASME Sect. III	Analysis	Compact, Rigid	High Freq.	Static Coefficient Analysis generally conducted.
17	Small Motor Operated Valves	Misc. Locations	Flow Isolation and Control	ANSI B16.9 ASME Sect. III	Analysis, Test or Both.	Rigid Body with Extended Operator	Med. Freq.	Simple dynamic models used to calculate response or testing conducted.

TABLE 9.0-1 - Continued

Item No.	GENERIC COMPONENT OR SUBSYSTEM	LOCATION IN PLANT	FUNCTION (1) OF EQUIPMENT	GOVERNING (2) CODE OR STANDARD	QUALIFICATION METHOD	SIZE/SHAPE OF EQUIPMENT	RESPONSE (3) CHARACTERISTICS	COMMENTS
18	Misc. Small Valves< 8"	Misc. Locations	Flow isolating + control (Active)	ANSI B16.9 ASME Sect. III for Body. IEEE 344 for Elect. Motor.	Analysis, Test or Both.	Compact, Rigid	High Freq.	Includes pneumatic, hydraulic, Squid and motor actuated isolation and control valves.
19	Large Cooling Fans, Motor Generators and Electric Motors	Misc. Locations	(Active)	AE Criteria IEEE 344	Analysis or test	Compact, Rigid Members	Med. - High Freq.	Analysis by simple dynamic model or static coefficient method.
20	Emergency AC Power Units (Diesel Generators)	Aux. Bldg.	Generate AC power (Active)	AE Criteria IEEE 344 for Electrical plus Industrial stds. for Mech.	Combined Analysis and Test	Skid Mounted Rigid Equip. Items.	Med. - High Freq.	Complex system of diesel engine, Alternator + ancilliary equipment. Several frequencies in amplified accel. regime.
21	DC Power Units (Batteries & Static Charger.	Aux. Bldg.	Provide DC Power (Passive)	AE Criteria IEEE 344	Test of Elect. Anal. of Supports	Framed Structures & Compact Equipment	Med. - High Freq.	Simple response analysis for battery racks, etc.
22	Switchgear	Aux. Bldg.	Active	AE Criteria IEEE 344 for Electrical, AISC for Structure	Test plus Analysis	Rack Mounted	Med. - High	Complex Electrical System enclosed by framed structure.

TABLE 9.0-1 - Continued

Item No.	GENERIC COMPONENT OR SUBSYSTEM	LOCATION IN PLANT	FUNCTION (1) OF EQUIPMENT	GOVERNING(2) CODE OR STANDARD	QUALIFICATION METHOD	SIZE/SHAPE OF EQUIPMENT	RESPONSE (3) CHARACTERISTICS	COMMENTS
23	Misc. Motor Control Centers, Inst. Racks. H & V + AC Controls, Aux. Relay Cabinets, Breakers. Local Instruments, heaters, Inverters, etc.	Misc. Locations	Active	AE Criteria IEEE 344 for Electrical, AISC for Racks.	Test or Analysis	Rack, mounted Electrical Equipment	Med. - High Freq.	Racks sometimes qualified by analysis. Electronic gear and instruments almost always qualified by test.
24	Cable Trays	Misc. Locations	Passive	AISC	Analysis	Beam like structures	Med. Freq.	Damping from cables likely much greater than used in response analysis.
25	Ducting	Misc. Locations	Passive	AISC	Analysis	Beam like structures	Med. to High Freq.	Thin wall rectangular and cylindrical sections.

TABLE 9.0-2 FRAGILITY DESCRIPTIONS

(From Ref. 355)

GENERIC CATETORY	SPECIFIC COMPONENT	FAILURE MODE	FUNDAMENTAL FREQUENCY Hz	FRAGILITY PARAMETER	MEDIAN DAMPING, % OF CRITICAL	MEDIAN CAPACITY	LOGARITHMIC STD. DEVIATION			RANK OF SOURCE
							COMPOSITE β_C	RANDOM β_R	UNCERTAINTY β_U	
Reactor Coolant System Class 1 Vessels and Supports	Reactor Pressure Vessel	Fracture of RPV Outlet Nozzle Safe End	5 (NSSS System)	Moment (in-lbs)	NA	2.12×10^8 in-lbs	0.36	0.21	0.29	5
Reactor Coolant System Class 1 Vessels and Supports	Steam Generator	Support Column Failure	5 (NSSS System)	Spectral Acceleration	5	5.2 g	0.34	0.14	0.31	5
Reactor Coolant System Class 1 Vessels and Supports	Pressurizer	Support Skirt Bolting	18-22	Spectral Acceleration	5	2.0 g	0.31	0.14	0.28	5
Reactor Coolant System Class 1 Vessels and Supports	Reactor Internals	Deformation of Guide Tube at Tube/Guide Plate Weld	5-15	Spectral Acceleration	5	2.75 g	0.24	0.14	0.19	5
Control Rods and Drives	Control Rod Housing	Control Rod Housing Deformation	6	Spectral Acceleration	5	6.0 g	0.24	0.14	0.19	5
Main Coolant Pumps	Reactor Coolant Pump	Support Column Failure	5 (NSSS System)	Spectral Acceleration	5	3.3 g	0.34	0.14	0.31	5
NSSS Piping	Generic Treatment	Fracture at RPV Outlet Nozzle	5 (NSSS System)	Moment (in-lbs)	NA	See Master Fragility Curve	0.37	0.21	0.30	4
Large Diameter Piping, 8" and Greater	Generic Treatment	Collapse	Variable	Moment (in-lbs)	NA	See Master Fragility Curve	0.37	0.21	0.30	4
Intermediate Diameter Piping, 2½"-8"	Generic Treatment	Collapse	Variable	Moment (in-lbs)	NA	See Master Fragility Curve	0.37	0.21	0.30	4

TABLE 9.0-2 - Continued

GENERIC CATETORY	SPECIFIC COMPONENT	FAILURE MODE	FUNDAMENTAL FREQUENCY Hz	FRAGILITY PARAMETER	MEDIAN DAMPING, % OF CRITICAL	MEDIAN CAPACITY	LOGARITHMIC STD. DEVIATION			RANK OF SOURCE
							COMPOSITE β_C	RANDOM β_R	UNCERTAINTY β_U	
Large Vertical Vessels and Heat Exchangers with Formed Heads	Generic Treatment	Support Failure or Nozzle Failure	Rigid	Zero Period Acceleration	NA	See Table 4-3	0.46	0.21	0.41	4
Large Vertical Vessels and Heat Exchangers with Formed Heads	Accumulator Tanks	Support Skirt Collapse	20.7	Spectral Acceleration	5	21.9 g	0.37	0.14	0.34	5
Large Vertical Vessels and Heat Exchangers with Formed Heads	RHR Heat Exchanger	Plastic Buckling of Shell	6.3	Spectral Acceleration	5	7.9 g	0.24	0.15	0.19	5
Large Flat Bottom Storage Tanks	Condensate Storage Tank	Buckling of Tank Wall at Base	Rigid Tank + Slosh	Zero Period Acceleration	NA	0.9 g	0.27	0.16	0.22	5
Large Flat Bottom Storage Tanks	Diesel Oil Storage Tank	Bending of Vertical Stiffener	Rigid Tank + Slosh	Zero Period Acceleration	NA	3.6 g	0.37	0.20	0.31	5
Large Horizontal Vessels and Heat Exchangers	Component Cooling Water Heat Exchanger	Support Failure	6.9	Spectral Acceleration	5	5.8 g	0.33	0.14	0.30	5
Large Horizontal Vessels and Heat Exchangers	Generic	Support Failure or Nozzle Failure	Rigid	Zero Period Acceleration	NA	See Table 4-3	0.46	0.21	0.41	4
Small-Medium Vessels and Heat Exchangers	Boron Injection Tank	Support Leg Failure	12.8	Spectral Acceleration	5	7.2 g	0.37	0.14	0.34	5
Small-Medium Vessels and Heat Exchangers	Generic	Support Failure or Nozzle Failure	Rigid	Zero Period Acceleration	NA	See Table 4-3	0.44	0.21	0.39	4
Buried Pipe	Service Water From Crib House	Buckling and Fracture	NA	Zero Period Acceleration	NA	1.4 g	0.42	0.17	0.39	5

TABLE 9.0-2 - Continued

GENERIC CATETORY	SPECIFIC COMPONENT	FAILURE MODE	FUNDAMENTAL FREQUENCY Hz	FRAGILITY PARAMETER	MEDIAN DAMPING, % OF CRITICAL	MEDIAN CAPACITY	LOGARITHMIC STD. DEVIATION			RANK OF SOURCE
							COMPOSITE β_C	RANDOM β_R	UNCERTAINTY β_U	
Buried Pipe	Aux. Feedwater From Condensate Storage Tank	Buckling and Fracture	NA	Zero Period Acceleration	NA	1.4 g	0.42	0.17	0.39	5
Large Vertical Centrifugal Pumps with Motor Drive	Service Water Pumps	Bending of Pump Casing	7	Spectral Acceleration	5	3.7 g	0.21	0.14	0.15	4
Small-Medium Horz. & Vert. Mtr., Turbine & Diesel Driven Pumps & Compressors	Residual Heat Removal Pump	Impeller Deflection	7	Spectral Acceleration	5	3.2	0.11	0.05	0.10	5
Small-Medium Horz. & Vert. Mtr., Turbine & Diesel Driven Pumps & Compressors	Residual Heat Removal Pump	Mounting Bolt Failure	7	Spectral Acceleration	5	11.7	0.27	0.15	0.22	5
Small-Medium Horz. & Vert. Mtr., Turbine & Diesel Driven Pumps & Compressors	Safety Injection Pump	Flange Bending	Rigid	Zero Period Acceleration	NA	3.4 g	0.35	0.14	0.32	5
Small-Medium Horz. & Vert. Mtr., Turbine & Diesel Driven Pumps & Compressors	Safety Injection Pump	Shaft Binding	Rigid	Zero Period Acceleration	NA	5.25 g	0.17	0.14	0.10	5
Small-Medium Horz. & Vert. Mtr., Turbine & Diesel Driven Pumps & Compressors	Centrifugal Charging Pump	Thrust Bearing Failure	Rigid	Zero Period Acceleration	NA	6.0 g	0.23	0.15	0.17	5
Small-Medium Horz. & Vert. Mtr., Turbine & Diesel Driven Pumps & Compressors	Centrifugal Charging Pump	Shaft Deflection	Rigid	Zero Period Acceleration	NA	28.9 g	0.21	0.15	0.15	5

TABLE 9.0-2 - Continued

GENERIC CATETORY	SPECIFIC COMPONENT	FAILURE MODE	FUNDAMENTAL FREQUENCY Hz	FRAGILITY PARAMETER	MEDIAN DAMPING, % OF CRITICAL	MEDIAN CAPACITY	LOGARITHMIC STD. DEVIATION COMPOSITE β_C	RANDOM β_R	UNCERTAINTY β_U	RANK OF SOURCE
Small-Medium Horz. & Vert. Mtr., Turbine & Diesel Driven Pumps & Compessors	Generic Pumps & Compressors	Generic Function	Rigid	Zero Period Acceleration	NA	26 g	0.21	0.15	0.15	2
Large Motor Operated Valves	Generic	Functional Due to Distortion of Extended Operator Structure	Rigid	Piping Peak Acceleration	NA	6.3 g	0.6	0.2	0.57	4
Large Hydraulic & Air Operated Valves	Main Steam Isolation Valve	Oil Reservoir Hold Down Bolts	Rigid	Zero Period Acceleration	NA	7.3 g	0.3	0.14	0.26	5
Large Hydraulic & Air Operated Valves	Generic	Generic Function	Rigid	Zero Period Acceleration	NA	35 g	0.31	0.2	0.24	2
Large Check, Spring Relief & Manual Valves	Generic	Generic Function	Rigid	Piping Peak Acceleration	NA	38 g	0.32	0.20	0.25	2
Small Motor Operated Valves ≤8"	Generic	Functional Due to Distortion of Extended Operators	Rigid	Piping Peak Acceleration	NA	8.2 g	0.6	0.2	0.57	4
Small Miscellaneous Valves ≤8"	Generic	Generic Function	Rigid	Piping Peak Acceleration	NA	38 g	0.31	.20	.24	2
Emergency A.C. Power Units	Generator Control Panel	Relay Chatter	30	Spectral Acceleration	5	0.95 g	0.24	0.15	0.19	6
Emergency A.C. Power Units	Engine Control Panel	Failed Relay	11	Spectral Acceleration	5	2.0 g	0.25	0.15	0.20	6
Emergency A.C. Power Units	Engine Control Panel	Operspeed Shutdown Valve Trip	22	Spectral Acceleration	5	0.75 g	0.3	0.17	0.25	6

TABLE 9.0-2 - Continued

GENERIC CATETORY	SPECIFIC COMPONENT	FAILURE MODE	FUNDAMENTAL FREQUENCY Hz	FRAGILITY PARAMETER	MEDIAN DAMPING, % OF CRITICAL	MEDIAN CAPACITY	LOGARITHMIC STD. DEVIATION			RANK OF SOURCE
							COMPOSITE β_C	RANDOM β_R	UNCERTAINTY β_U	
Emergency A.C. Power Units	Engine & Generator Components	Structural	Rigid	Zero Period Acceleration	NA	>6.5 g	0.5	0.3	0.4	4
Emergency D.C. Power Units	Battery Rack	Anchor Bolts	8	Spectral Acceleration	5	12.5 g	0.3	0.21	0.24	5
Emergency D.C. Power Units	Batteries	Case Cracking & Plate Failure	8	Spectral Acceleration	5	4.2 g	0.16	0.1	0.12	6
Switch Gear	4160 & 480 Volt Units	Relay Chatter	5-10	Spectral Acceleration	5	2.07 g	1.46	0.5	1.37	6
Switch Gear	4160 & 480 Volt Units	Breaker Trip	5-10	Spectral Acceleration	5	7.7 g	0.73	0.4	0.61	6
Switch Gear	4260 & 480 Volt Units	Structural	5-10	Spectral Acceleration	5	14.6 g	0.8	0.4	0.69	6
Transformers	Generic	Structural	5-10	Spectral Acceleration	5	10.7 g	0.21	0.1	0.18	2
Local Instruments & Transmitters	Generic	Electrical Function	Rigid	Zero Period Acceleration	NA	37.8 g	0.32	0.2	0.25	6
Instrument Panels & Racks	Generic	Relay Chatter	5-10	Spectral Acceleration	5	2.07 g	1.46	0.5	1.37	6
Instrument Panels & Racks	Generic	Breaker Trip	5-10	Spectral Acceleration	5	7.7 g	0.73	0.4	0.61	6
Instrument Panels & Racks	Generic	Structural	5-10	Spectral Acceleration	5	14.6 g	0.8	0.4	0.69	6
Control Panels and Racks	Reactor Protection System	Functional-Electrical Manfunction	5-10	Spectral Acceleration	5	16 g	0.35	0.2	0.29	6
Control Panels and Racks	Generic	Relay Chatter	5-10	Spectral Acceleration	5	2.07 g	1.46	0.5	1.37	6

TABLE 9.0-2 - Continued

GENERIC CATETORY	SPECIFIC COMPONENT	FAILURE MODE	FUNDAMENTAL FREQUENCY Hz	FRAGILITY PARAMETER	MEDIAN DAMPING, % OF CRITICAL	MEDIAN CAPACITY	LOGARITHMIC STD. DEVIATION			RANK OF SOURCE
							COMPOSITE β_C	RANDOM β_R	UNCERTAINTY β_U	
Control Panels and Racks	Generic	Breaker Trip	5-10	Spectral Acceleration	5	7.7 g	0.73	0.4	0.61	6
Control Panels and Racks	Generic	Structural	5-10	Spectral Acceleration	5	14.6 g	0.8	0.4	0.69	6
Relay Cabinets	Generic	Relay Chatter	5-10	Spectral Acceleration	5	2.07 g	1.46	0.5	1.37	6
Relay Cabinets	Generic	Relay Trip	5-10	Spectral Acceleration	5	7.7 g	0.73	0.4	0.61	6
Relay Cabinets	Generic	Structural	5-10	Spectral Acceleration	5	14.6 g	0.8	0.4	0.69	6
Motor Control Centers	Generic	Relay Chatter	5-10	Spectral Acceleration	5	2.07	1.46	0.5	1.37	6
Motor Control Centers	Generic	Breaker Trip	5-10	Spectral Acceleration	5	7.7 g	0.73	0.4	0.61	6
Motor Control Centers	Generic	Structural	5-10	Spectral Acceleration	5	14.6 g	0.8	0.4	0.69	6
Breaker Panels	Generic	Breaker Trip	5-10	Spectral Acceleration	5	7.7 g	0.73	0.4	0.61	6
Breaker Panels	Generic	Structural	5-10	Spectral Acceleration	5	14.6	0.8	0.4	0.69	6
Static Inverters	Zion Specific Static Inverter	Relay Trip	5-10	Spectral Acceleration	5	16 g	0.35	0.2	0.29	6
Air Conditioning & Air Handling Power Units	Containment Fan Coolers	Rubbing of Fan on Housing	4.3	Spectral Acceleration	5	2.0 g	0.23	0.15	0.17	5

TABLE 9.0-2 - Continued

GENERIC CATETORY	SPECIFIC COMPONENT	FAILURE MODE	FUNDAMENTAL FREQUENCY Hz	FRAGILITY PARAMETER	MEDIAN DAMPING, % OF CRITICAL	MEDIAN CAPACITY	LOGARITHMIC STD. DEVIATION			RANK OF SOURCE
							COMPOSITE β_C	RANDOM β_R	UNCERTAINTY β_U	
Air Conditioning & Air Handling Power Units	Containment Fan Coolers	Rubbing of Motor Rotor on Housing	4.3	Spectral Acceleration	5	2.14 g	0.24	0.15	0.19	5
Air Conditioning & Air Handling Power Units	Generic	Generic Functions	10-30	Spectral Acceleration	5	9.5 g	0.24	0.15	0.19	6
Ducting	Generic	Structural Failure of Supports	Reference to ZPA	Zero Period Acceleration	NA	See Table 2-4	0.39	0.18	0.35	4
Cable Trays	Generic	Cable Support System	Fragility Referenced to ZPA	Zero Period Acceleration	NA	3 g	0.55	0.3	0.46	4
Off Site Power	Ceramic Insulators	Fracture of Insulators	Referenced to Ground ZPA	Peak Ground Acceleration	NA	0.2 g	0.32	0.20	0.25	4

Note: Rank of source based on following criteria

(a) Range is 1-6 with 1 being the least credible source.

(b) For generic equipment ranked 2, the information source is from short duration (2-5 sec) shock type tests and the failure modes are structural. The low ranking reflects the author's personal feeling that the energy content of the shock tests is not indicative of earthquake-type loading and that the fragility levels may be biased upward compared to actual fragilities of equipment subjected to a seismic input.

(c) A ranking of 4 reflects an analytical derivation of generic structural capacity of equipment designed to specific codes and standards or test data or historical earthquake data with limited documentation.

(d) A ranking of 5 reflects an analytical derivation of fragility, either structural or functional, for specific components for which design reports were reviewed or for which new analyses were conducted.

(e) A ranking of 6 reflects fragility descriptions developed from either fragility tests on plant specific or generic components or fragility descriptions developed from high shock level qualification tests utilizing the U.S. Corps. of Engineers Pseudo-probabilistic methodology to develop fragility descriptions.

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EVALUATION OF METHODOLOGY FOR SEISMIC QUALIFICATION OF NUCLEAR PLANT ELECTRICAL AND MECHANICAL EQUIPMENT

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Report No. SwRI 6582-001-02
Contract NRC-04-81-185
Task 1 Summary Report Part II

Prepared For
U. S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, D. C. 20555

February 1, 1983

Approved:

H. Norman Abramson, Vice President
Engineering and Materials Sciences

Part II

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PREFACE

This report represents one of a series which is to present the results of a research program that is being conducted to evaluate methodology of equipment seismic qualification for nuclear plants. The overall program consists of the following subtasks:

1.1, 1.2, 1.3	Review methodology, aging, and static loads; Identify anomalies
1.4	Evaluate multiple frequency excitations
1.5	Consider combined dynamic environments
1.6	Develop in-situ test criteria
1.7	Study procedures for line mounted items
1.8	Publish Task 1 Summary Report
2.1, 2.2, 2.3	Investigate response level and multiple-parameter correlations
2.4, 2.5	Consider single parameter and damage severity factor correlations
2.6	Develop general correlation method
2.7	Publish Task 2 Summary Report
3.1	Recommend updating of qualification criteria
3.2	Publish Task 3 Summary Report
4.1, 4.2	Compile fragility data
4.3	Evaluate and reduce data
4.4	Publish Task 4 Summary Report

Specifically, this document constitutes Part II of the report identified above in Subtask 1.8. It, along with Part I which has already been published, presents results which have been compiled under Task 1, except for Subtask 1.7. Efforts on the latter subtask have been delayed, and will be included in a later summary report. Work on the other tasks is in progress, and will be reported in the later-indicated summary reports.

PRINCIPAL NOTATION

a^*	denotes peak value of acceleration time history
$\bar{a}_i$	acceleration, time average over time interval i
$\bar{a}_o$	acceleration, time average over complete seismic event
$\bar{a}_{sm}$	acceleration, time average over strong motion
$\bar{a}_{max}$, $\bar{a}_{min}$	maximum or minimum $\bar{a}_i$ during complete seismic event
B_e	effective bandwidth of analysis
[C]	damping matrix
$E(m_i)$	error function for off diagonal modal masses
f	frequency
$F(m_i)$	optimization function for physical masses
{F}	matrix of externally applied forces
$G_x(f)$	power spectral density (PSD) for motion at point x
$G_j(\omega)$	base excitation PSD in j direction
$G(f)_{max}$, $G(f)_{min}$	extreme values of acceleration PSD (as a function of frequency) that occurred within any time interval during strong motion
G_{max}, G_{min}	value of $G(f)_{max}$, $G(f)_{min}$ averaged over frequency range
$G_o(f)$	acceleration PSD (as a function of frequency) for complete strong motion
G_o	value of $G_o(f)$ averaged over frequency range
h_{rj}	transfer function for mode r due to base excitation in j direction
$H_{xy}(f)$	transfer function for response at y due to excitation at x (both x and y in same direction)
$H_{ij}^k(\omega)$	transfer function for response in k direction at point i, with excitation in j direction
i	$\sqrt{-1}$ in Eqs. 6-12, 6-13 only
i,j,k	indices
k_{rr}	modal stiffness for mode r
[K]	stiffness matrix
m_i	physical mass at node i of finite element model
$\tilde{m}_{pq}$	estimated modal mass for mode r
m_{rr}	modal mass for mode r

m_{pq}	off diagonal elements of modal mass matrix
M_o	total mass of finite element structure
$[M]$	mass matrix
N	number of nodal points in finite element model
N_n	nonstationarity number
N_s	number of sample averages
p,q,r	indices
S	step size for mass optimization scheme
$S_a(f_r)$	acceleration response spectrum at frequency r
T_B	duration of sample block time
$[T]$	transformation matrix which relates motion at structural nodes to base excitation
$\{u\}$	nodal relative displacement vector
$\{w\}$	base motion displacement vector, $\lfloor X,Y,Z,\theta_x,\theta_y,\theta_z \rfloor$
$\{x\}$	nodal absolute displacement vector
y^*	peak value of a response

α	weighting coefficient for time history synthesis
β	equivalent viscous damping ratio
β_r	modal damping ratio for mode r
γ	weighting factor for mass smoothing scheme
γ_r	modal participation factor for mode r
η_r	generalized displacement for mode r
$\{\phi_r\}$	eigenvector for mode r
$[\phi]$	matrix of R eigenvectors
Φ_{ik}	product of eigenvector components
ω	circular frequency
ω_r	natural circular frequency for mode r

1.0 INTRODUCTION

1.1 Overview

A research and development program is being conducted to review and evaluate methods of seismic qualification of nuclear plant equipment, correlate the methods with existing criteria, and recommend where both methods and criteria may be revised to provide more effective implementation of the qualification process. Task 1 of this program was initiated with an extensive review of the background and state-of-the-art study of the methodology and criteria for equipment qualification. Although the emphasis was on seismic and dynamic environments, information was also obtained for thermal, nuclear radiation, and other effects. The results of this review have been compiled and published as Reference [1], which constitutes Part I of the Task 1 Summary Report for the program. Included in Reference [1] are a summary of the approaches to qualification, a list of equipment which is typically involved in the qualification process and procedures used to qualify them, and an identification of a series of technical issues/anomalies which may have an influence on the final validity of the qualification methodology.

This document constitutes Part II of the Task 1 Summary Report, and includes the results of additional efforts that were conducted to provide an in-depth evaluation of the technical issues/anomalies previously identified. Both analytical and experimental studies were performed on a typical local instrument rack, in order to evaluate the impact of many of the identified issues. For convenience, a summary of these items is first given herein, followed by important background material on recent developments in relationships between response spectra and power spectra as parameters for earthquake motion description. This is followed by results from an extensive study of the fundamental criteria for earthquake simulation. Descriptions are then given for both analytical and experimental efforts for gathering response information for the electrical rack under various excitations. The remainder of the report covers extensive results on evaluation of the technical issues/anomalies, and in most cases includes conclusions on the impact of the results on current qualification criteria. Implications of the results for qualification of most types of equipment are included where appropriate.

1.2 Summary of Technical Issues/Anomalies

At the outset, it must be recognized that the definition of the term technical "issue/anomaly" as used herein includes the occurrence of an unexplained variation of results in qualification. It is paramount to recognize that these issues/anomalies may or may not be significant in influencing the validity of the qualification process. Furthermore, each cited item does not apply to qualification in general, but only to certain cases. As a further clarification, it is extremely important to point out that this identification of technical issues/anomalies must not be taken to imply that any of the equipment qualification performed to date is necessarily inadequate. On the contrary, early seismic test programs recognized that the test methods did not necessarily provide a close simulation of the actual seismic event and, consistent with good engineering practice, qualification testing was accomplished with a degree of conservatism which was judged sufficient to cover the uncertainties. In fact, further study of the issues/anomalies will help reveal to what degree conservatism has been present, and may even allow relaxation of some requirements as a result.

The existence of the technical issues/anomalies was simply noted in Reference [1], while further evaluation of their importance was subsequently accomplished, and the results are presented herein. A summary of the identified items is given for convenience in Table 1-1. They are separated into those which pertain to methodology which affects all equipment in general, and those which are peculiar to a given equipment subgroup. Herein, attention is given principally to the former group which can affect all equipment concerned. Details of the listed items can be obtained from Reference [1], and therefore will not be repeated here. However, the essence of many of them are obvious from the phrasology, and further details will become apparent from discussions presented herein.

TABLE 1-1
TECHNICAL ISSUES/ANOMALIES IN QUALIFICATION OF NUCLEAR PLANT EQUIPMENT*

QUALIFICATION METHODOLOGY

1.0 Qualification by Testing

- 1.1 Uncertainties in Use of Response Spectrum
- 1.2 Effects of Cross Coupling
- 1.3 Comparison of Test Severities
- 1.4 Nonlinearities
- 1.5 Test Sequence
- 1.6 Methods for Dynamic Load Combination
- 1.7 Fragility

2.0 Qualification by Analysis

- 2.1 Degree of Model Complexity
- 2.2 Synthesis of Damping
- 2.3 Acceptance Criteria

3.0 Combined Experimental and Analytical Qualifications

- 3.1 Validation and Refinement of Analytical Models
- 3.2 In Situ Testing

4.0 Synergistic Effects and Aging

- 4.1 Test Sequence
- 4.2 Aging Methods
- 4.3 Arrhenius Model

EQUIPMENT SUBGROUPS

5.0 Fragility Data for Most Equipment

6.0 Aging Data for Most Equipment

7.0 Liquid Vessels and Submerged Structures

8.0 Large and Small Piping

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*From Review Report, Ref. [1]

2.0 RESPONSE SPECTRUM/POWER SPECTRUM RELATIONSHIPS

2.1 General Comments

The response spectrum has typically been used since the 1930's to estimate the peak response of structures to an earthquake motion. Inherently, it also then is used as a parameter to describe the earthquake motion itself, through its effects on a single degree of freedom oscillator. Thus, its properties as an earthquake descriptive parameter must be understood carefully for its use in seismic qualification of equipment, whether done by test or by analysis. Earthquake motions can also be described similarly by power spectral density functions, which provide a description of the energy content of the motion itself, without any reference to the effects of the motion on a structure. Although the use of either parameter for the description of an earthquake is analogous, it is often more useful to use one or the other because of their specific mathematical properties.

In this study it has been found useful to use the two parameters as complementary tools, where a transformation between them exists. Since this philosophy has only recently become more commonplace in the earthquake community, some discussion will be presented before moving to the main results of this report. The concept of the response spectrum/power spectrum transformation was not originated under this program, but was developed just prior to its initiation.

2.2 Response Spectrum

The response spectrum is recognized to represent a plot of the peak response of a series of single degree of freedom oscillators with specified natural frequencies, when all oscillators include the same damping, and their bases are subject to the same earthquake motion. Thus, the plot implicitly becomes a nonunique description of the motion that produced the responses. Furthermore, it is recognized that energy is present in the excitation only at those frequencies where amplification over the zero period acceleration (ZPA) occurs for the acceleration response spectrum.

For analysis purposes, the response spectrum can also be used to predict peak responses in complex structures by means of modal analysis techniques [2]. That is, the peak response y_r^* in mode r at some point y of a structure can be related to the excitation at some point x by the expression

$$y_r^* = 2\,\beta_r\,|H_{xy}(f_r)|\,S_a(f_r) \tag{2-1}$$

where β_r is the damping ratio for mode r, $H_{xy}(f_r)$ is the value for the linear transfer function for the response at y due to the input at x at the natural frequency f_r when computed for a damping ratio of β_r. If several modes are present, the total response at y can be estimated by a square root of the sum of the squares (SRSS) of the contribution of the response in each mode:

$$y^* = \{\sum_r [2\ \beta_r |H_{xy}(f_r)|\ S_a(f_r)]^2\}^{1/2} \qquad (2\text{-}2)$$

The above relationships are written in terms of the modal transfer function $H_{xy}(f_r)$. This is a form that is especially useful for experimental measurement. However, the relationships are equally valid for analysis, although in this case the modal participation factor γ_r is usually defined instead of the transfer function. The two are related by:

$$\gamma_r = \frac{2\beta_r}{\phi_r(y)}\ |H_{xy}(f_r)| \qquad (2\text{-}3)$$

where $\phi_r(y)$ is the magnitude of the rth mode eigenvector evaluated at point y.

It must be noted that only the peak value of the response is predicted by the above relationships. In order to predict a complete response spectrum at point y a time history solution of the structural equations is performed, and then a response spectrum computed from the response time history at point y. This approach is rather tedious, and is no longer necessary if a power spectral density approach is used.

2.3 Power Spectrum

A power spectral density expresses the mean square energy in a time history as a function of frequency. A relationship between the response power spectral density $G_y(f)$ at point y and the excitation power spectral density $G_x(f)$ at point x of a linear system subject to a stationary random process can be expressed as [3]:

$$G_y = |H_{xy}(f)|^2\ G_x(f) \qquad (2\text{-}4)$$

This relationship is convenient to use because it gives a plot of the energies as a function of frequency directly without the necessity of a time history solution. The peak response value can be determined statistically by the amplitude probability density function. However, it must be emphasized that the expression is valid only for a stationary random process. In this regard, it will be shown later that typical earthquake accelograms can be approximated as a stationary random process during their strong motion.

2.4 Transformation Between Spectra

In view of the fact that most earthquake data is developed in terms of response spectra, and yet it is very useful to use power spectra for some purposes, it becomes desirable to consider a transformation between response and power spectra and vice versa. Such a transformation has recently been developed by several investigators. Detailed application of the transformation for specific earthquake response has been reported by Sundararajan [4] and for problems in equipment qualification by Unruh and Kana [5]. An example of the transformation as developed in the latter reference is shown in Figure 2.4-1. A base response spectrum

(BRRS) was transformed to a power spectral density, and then transformed back to a response spectrum. The accuracy of the process is shown to be quite acceptable in five iterations.

The transformation process described in Reference [5] will be used several times in the results to follow herein. It will be found that the power spectral density is especially useful for identifying the frequency content of a time history, especially when a rather high peak value (ZPA) is present.

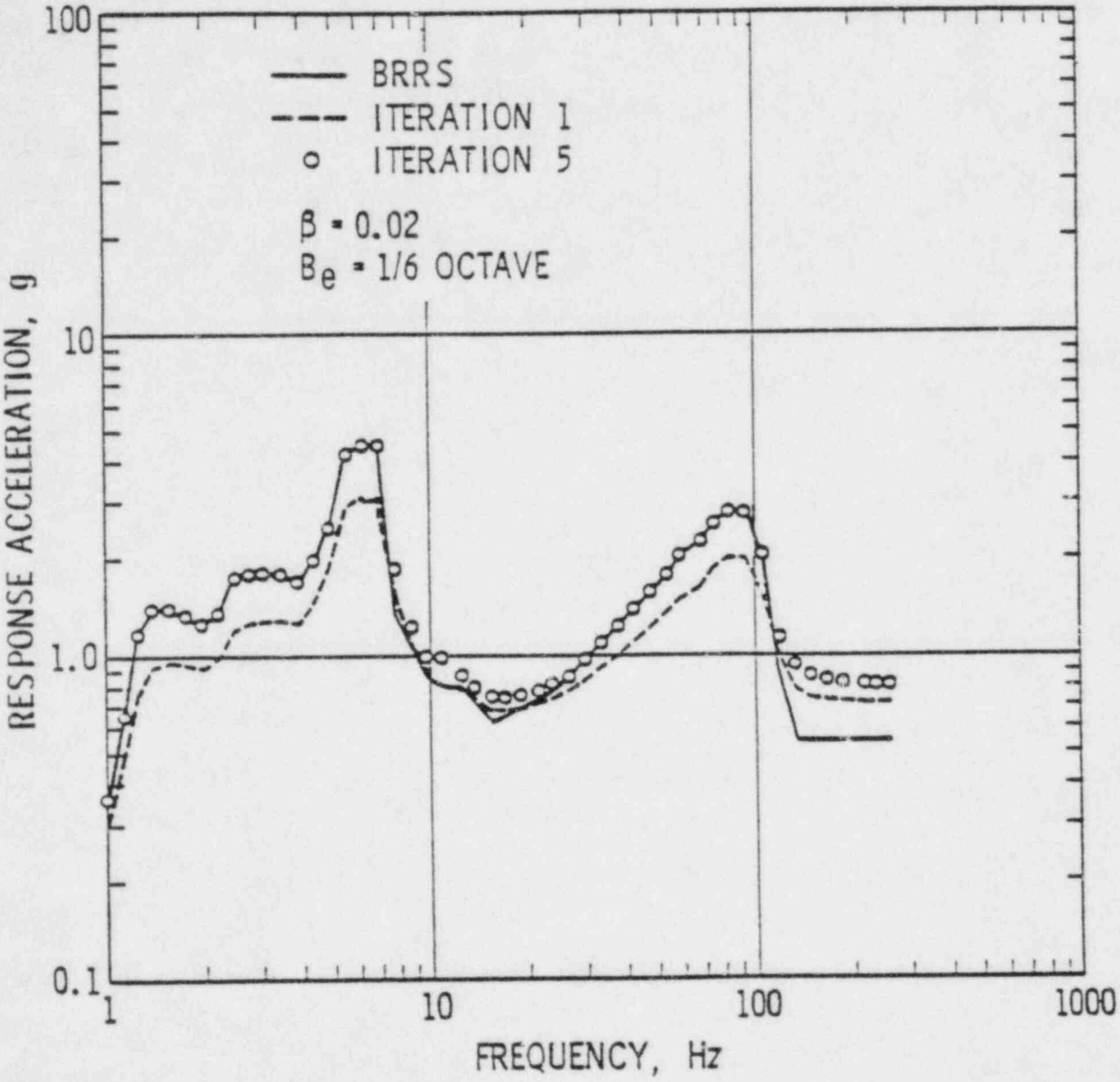

Figure 2.4-1. Convergence of Response/Power Spectrum Transformation (From Ref. [5])

3.0 FUNDAMENTAL CRITERIA FOR EARTHQUAKE SIMULATION

3.1 Ground Level Simulation

For equipment qualification purposes, IEEE 344 [6] includes several different recommended methods for generation of simulated earthquake environments. The major requirement is that the excitation time history should conservatively simulate the strong motion portion of a postulated earthquake event. Section 6.6 of IEEE 344 outlines a number of test methods which are acceptable, providing that the resulting motion satisfies the following:

1) Produces a TRS which closely envelopes the RRS.

2) Contains a peak acceleration greater than or equal to the ZPA of the RRS, except at low frequencies where the RRS is below the ZPA level.

3) Contains no energy at frequencies above that where the ZPA reaches its asymptote.

4) Is of the required duration (strong motion portion no less than fifteen seconds).

The above requirements indicate that the specification of an earthquake event is usually given in the form of a required response spectrum (RRS), and the generation of a time history which corresponds to the RRS is required. From this, several methods of generating time histories for analysis purposes are implied, and various techniques are specifically described for synthesizing test motions. Whatever the signal synthesis process, the net result should be such that the actual analysis or test response spectrum (TRS) envelopes the required response spectrum. This criterion must be observed for both ground level motions, which are recognized to have frequency content nominally between 1 and 33 hertz, and floor level spectra, which can have significant narrow-band frequency content, depending on the presence of building resonances.

Earlier work described in Reference [1] indicates that the above criteria can be met with time histories that vary widely from those of earthquakes. With the possibility of synthesizing the excitation by many different methods, it has become obvious that a closer look at earthquake fundamental characteristics was appropriate, even though actual enveloping of the RRS by a TRS may have been achieved. This will assure that the spirit of the enveloping requirement was maintained. The results of the study for ground level simulations are presented first in this section. Then some comments on floor level motion simulations follow. The study was based on the characteristics of the six representative earthquakes shown in Table 3-1. The selected statistical characteristics, given below, were deemed sufficient to provide a good approximation of earthquake motions at ground level. Although other such studies have been conducted in the past, this one was specifically aimed at determining those characteristics which are

TABLE 3-1

SAMPLE TIME HISTORIES USED FOR EARTHQUAKE CHARACTERISTICS STUDY

1. ELCENTRO SITE IMPERIAL VALLEY IRRIGATION DISTRICT
   IMPERIAL VALLEY EARTHQUAKE, MAY 18, 1940 - 2037 PST
   COMPONENTS - S00E
   - S90W
   - VERTICAL
2. TAFT LINCOLN SCHOOL TUNNEL
   KERN COUNTY, CALIF. EARTHQUAKE, JULY 21, 1952 - 0453 PDT
   COMPONENTS - N21E
   - S69E
   - VERTICAL
3. OLYMPIA, WASHINGTON HWY. TEST LAB
   WESTERN WASHINGTON EARTHQUAKE, APRIL 13, 1949 - 1156 PST
   COMPONENTS - N04W
   - N86E
   - VERTICAL
4. CHOLAME, SHANDON, CALIFORNIA ARRAY NO. 5
   PARKFIELD, CALIF. EARTHQUAKE, JUNE 27, 1966 - 2026 PST
   COMPONENTS - N05W
   - N85E
   - VERTICAL
5. HOLLYWOOD STORAGE BSMT. LOS ANGELES, CALIF.
   SAN FERNANDO EARTHQUAKE, FEB. 9, 1971 - 0600 PST
   COMPONENTS - S00W
   - N90E
   - VERTICAL
6. CALTECH MILLIKEN LIBRARY, BASEMENT, PASADENA, CALIF.
   SAN FERNANDO EARTHQUAKE, FEB. 9, 1971 - 0600 PST
   COMPONENTS - N00E
   - N90E
   - VERTICAL

most useful for earthquake motion simulation for equipment qualification purposes.

3.1.1 General Characteristics of Motion

Earthquake motions are known to be nonstationary transient random motion of various durations, the typical character of which are given by the El Centro 1940 time histories shown in Figure 3.1-1. Acceleration signals, rather than velocity or displacement signals, are usually used for describing both test and analysis motion. The general motion is such that a random acceleration signal is modulated by the envelope, an example of which is shown in Figure 3.1-2.* Singh [7] and others have agreed that a good simulation can be achieved by modulation of a stationary random process by such a function. This would mean that the simulation would be approximately stationary during the strong motion part of the earthquake, which is within the constant value portion of the envelope function in Figure 3.1-2. Thus, the several selected earthquakes were studied in such a way as to determine whether the above hypothesis is sufficiently correct for qualification purposes. Satisfaction of this hypothesis is important for both test and analysis methodology.

3.1.2 Definition of Strong Ground Motion

Surprisingly, Reference [8] indicates that no quantitative definition of the strong motion portion of an earthquake has been uniformly recognized by engineers. Herein, a definition was developed somewhat similar to the Trifunac-Brady duration [8]. For the present definition, time interval RMS values of the accelograms were calculated as shown by several examples in Figures 3.1-3 and 3.1-4. The dashed lines and numbers indicate overall RMS levels, $\bar{a}_0$, of the signal averaged over the entire time history. For this computation the data were started and stopped so that only the continuous signal greater than 1% of the peak acceleration was utilized (anything outside 1% was assumed to be noise). Then, time interval RMS values, $\bar{a}_i$, were averaged for a chosen time interval (for computational convenience 5.12 seconds was selected). Thereafter the strong motion portion was defined such that

$$\bar{a}_i/\bar{a}_0 \geq 1.25 \qquad (3\text{-}1)$$

Subsequently, any computation of parameters for the strong motion (SM) portion of a given signal was performed only on that part of the time history that fell within this bound.

3.1.3 Frequency Content

Power spectral density was recognized to be a more sensitive parameter than the response spectrum for indicating frequency content of a signal, and was therefore used for this purpose. Furthermore, the concept of a time interval average PSD was well recognized and easily

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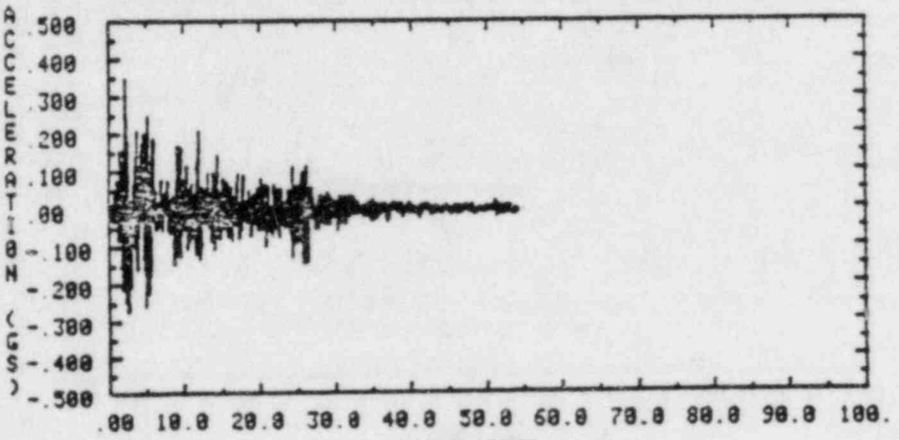
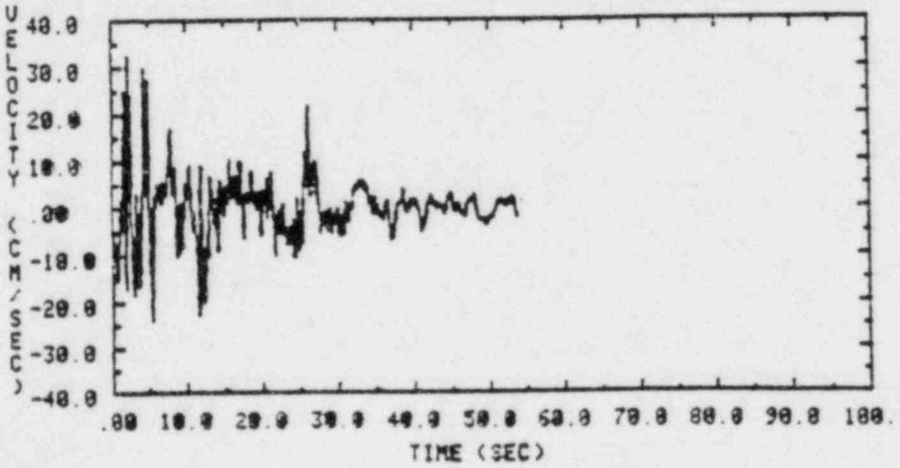
*Note that a minimum of fifteen seconds strong motion is specified by IEEE 344 [6].

EL CENTRO SITE IMPERIAL VALLEY IRRIGATION DISTRICT
COMP S00E
IMPERIAL VALLEY EARTHQUAKE MAY 18, 1940 - 2037 PST
PEAK ACCELERATION = 341.69531 CMS/SEC/SEC AT 2.1200 SEC



PEAK VELOCITY = 33.44914 CMS/SEC AT 2.1800 SEC



PEAK DISPLACEMENT = 10.36678 CMS AT 8.5800 SEC

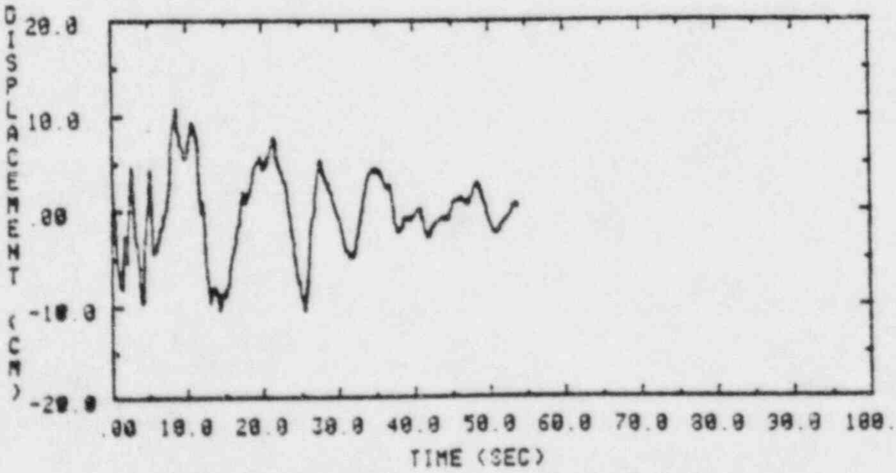


Figure 3.1-1. Typical Earthquake Time Histories

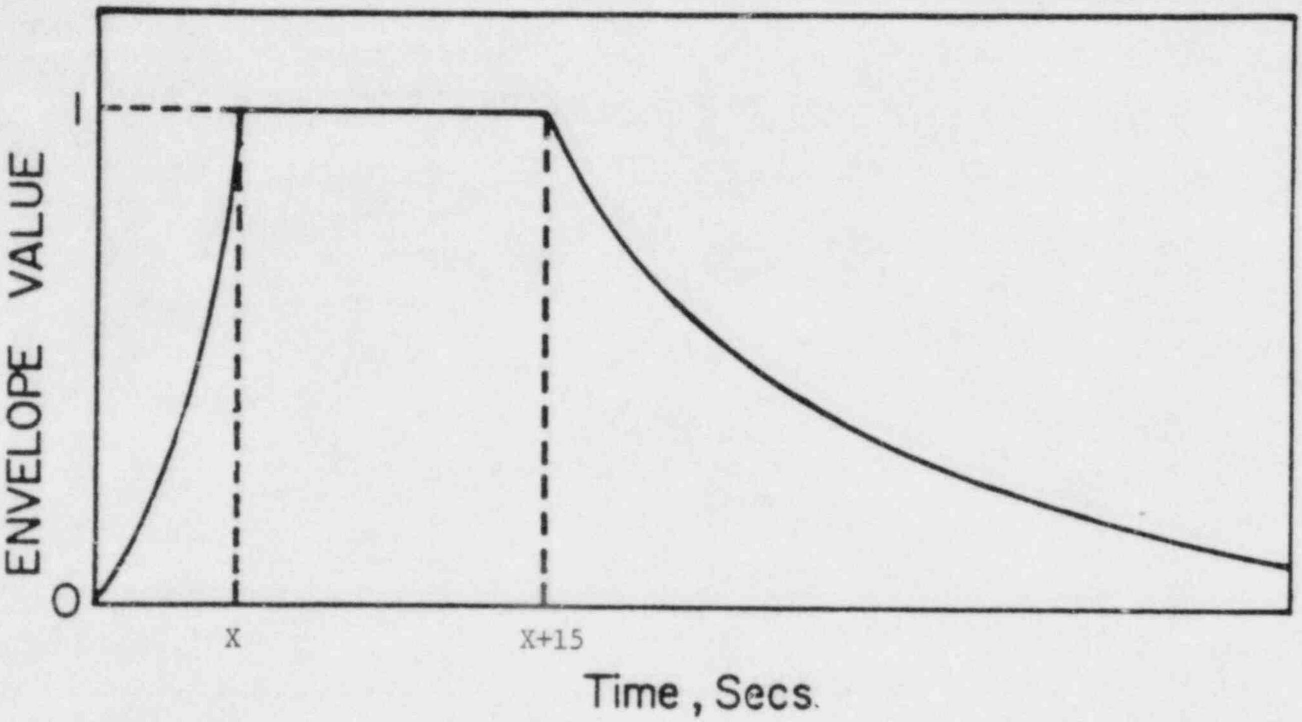


Figure 3.1-2. Sample Acceleration Intensity Modulation Function for Typical Earthquakes

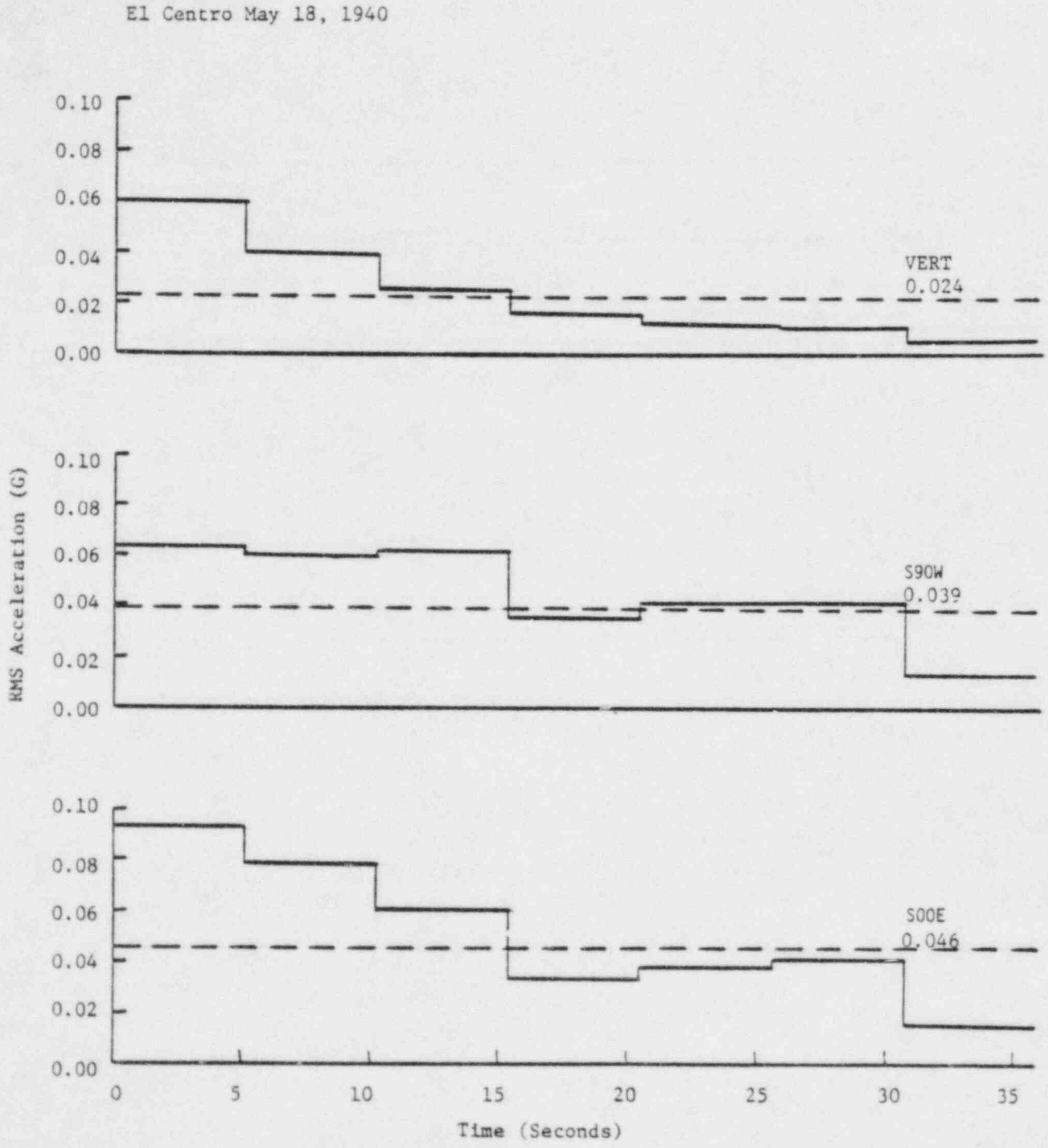


Figure 3.1-3. Time Interval RMS Acceleration for El Centro 1940

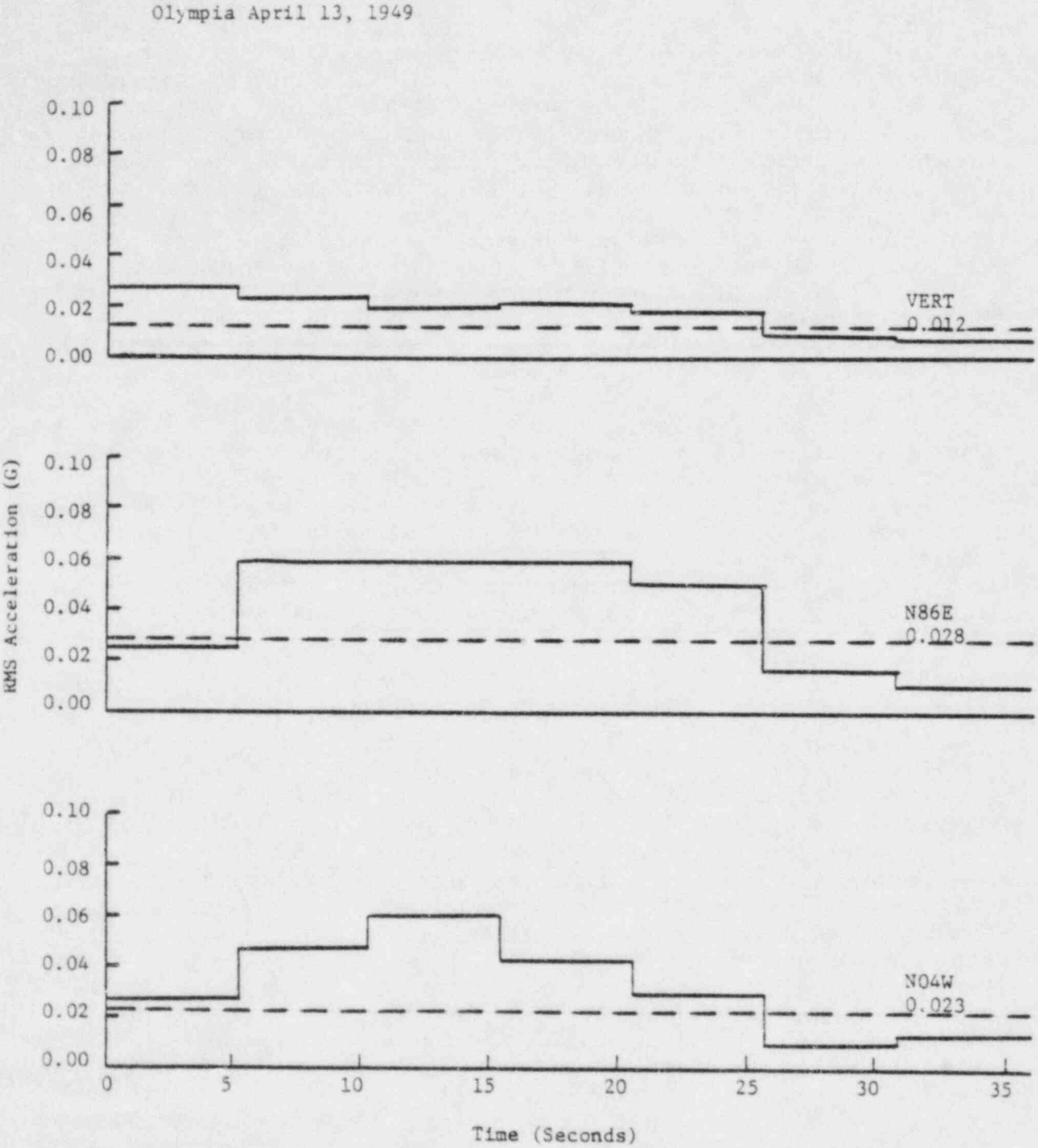


Figure 3.1-4. Time Interval RMS Acceleration for Olympia 1949

computed with available laboratory and digital equipment. Initially, such time interval PSD's were computed for the various sample earthquake components, as shown in Figures 3.1-5 and 3.1-6. Then, the composite PSD averaged only over the strong motion portion of the signal was determined, Figure 3.1-7. Note that this computation was performed on a fast Fourier transform (FFT) analyzer having a constant resolution bandwidth of 0.2 Hz. It is interesting to note that typical laboratory FFT analyzers are designed for analysis with selectable, but constant bandwidth resolution. Conversely, laboratory response spectrum analyzers are typically designed with selectable percentage (partial octave) bandwidth resolution. In any event, the corresponding parameters computed for the same signal can only be equivalent within the resolution of the analysis. For example, Figure 3.1-8 shows a PSD that was transformed from the 1/6 octave response spectrum of the same NS component of the 1940 El Centro earthquake whose directly computed PSD appears in Figure 3.1-7. Obviously the 1/6 octave resolution is coarser at higher frequencies, as should be expected. In general the average levels computed using both procedures agree very closely.

In any event, the PSD of the SM of typical earthquakes is a definite indication of the frequency content required for ground level simulations. Rather than reanalyze many earthquakes for PSD's and form some type of envelope, the development is easily accomplished by a transformation to a PSD from a response spectrum for the R.G. 1.60 [9] criteria. This has been done for a 1.0 g ZPA RRS as shown in Figures 3.1-9 and 3.1-10. Thus, a frequency content criteria for ground motion compatible with existing response spectra criteria has been established.

3.1.4 Stationarity

The degree of stationarity of the data during the strong motion portion of the signal had to be established to validate the hypothesis necessary for the development of Equation 2-4. For this study, stationarity was interpreted to mean the degree of fluctuation of the RMS and PSD level at a given frequency during a specified time. One recognized test for stationarity is to determine the number of runs in a sequence relative to a mean and compare them to expected values for a random variable [3]. If the earthquake signal is divided into fine blocks, 0.64 seconds duration, the strong motion portion will contain enough data samples to use the run test. The number of runs was determined using the mean and the RMS valves during the strong motion portion of the earthquake. This procedure was used for the six earthquakes studied in this program. Of a total of eighteen signals, twelve satisfied the requirements for a 0.05 level of significance, two satisfied the requirements for a 0.025 level of significance, two were not stationary and two could not be analyzed due to the short duration of the signal. These results clearly indicated sufficient stationarity for the data. However, it was decided that stationarity could be demonstrated even further by showing to what degree the PSD level fluctuation of the strong motion portion of the various earthquake components was similar to that of a typical stationary random signal. Details of this approach will now be described.

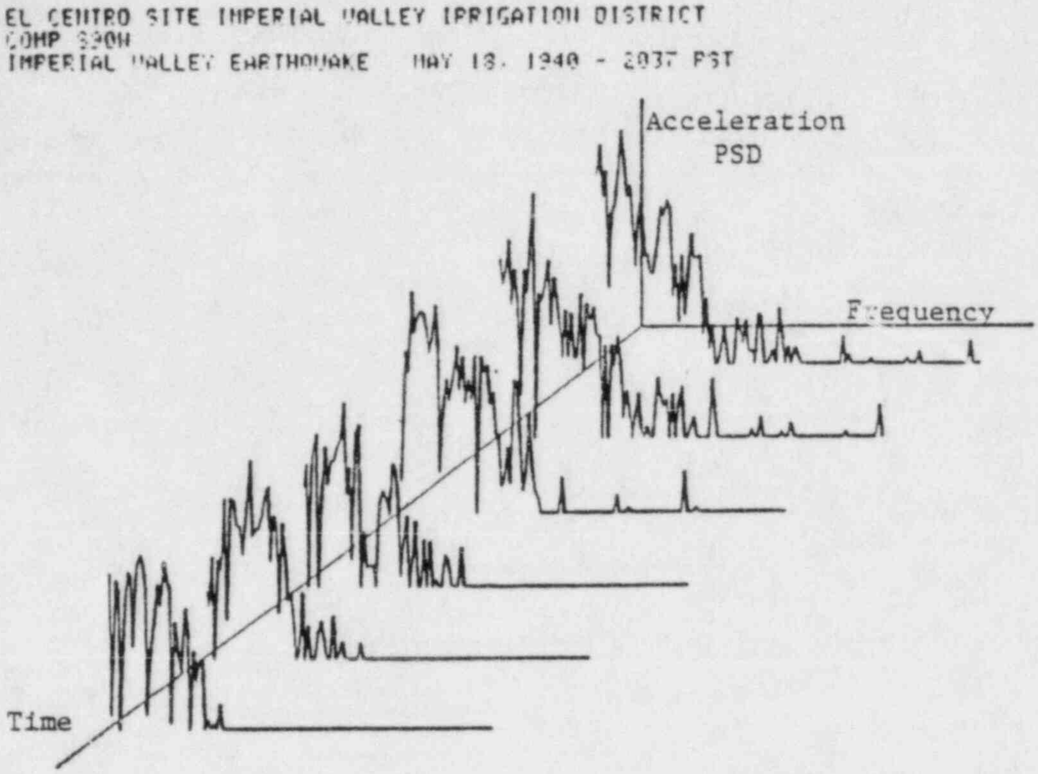


Figure 3.1-5. Time Interval PSD for El Centro 1940 EW

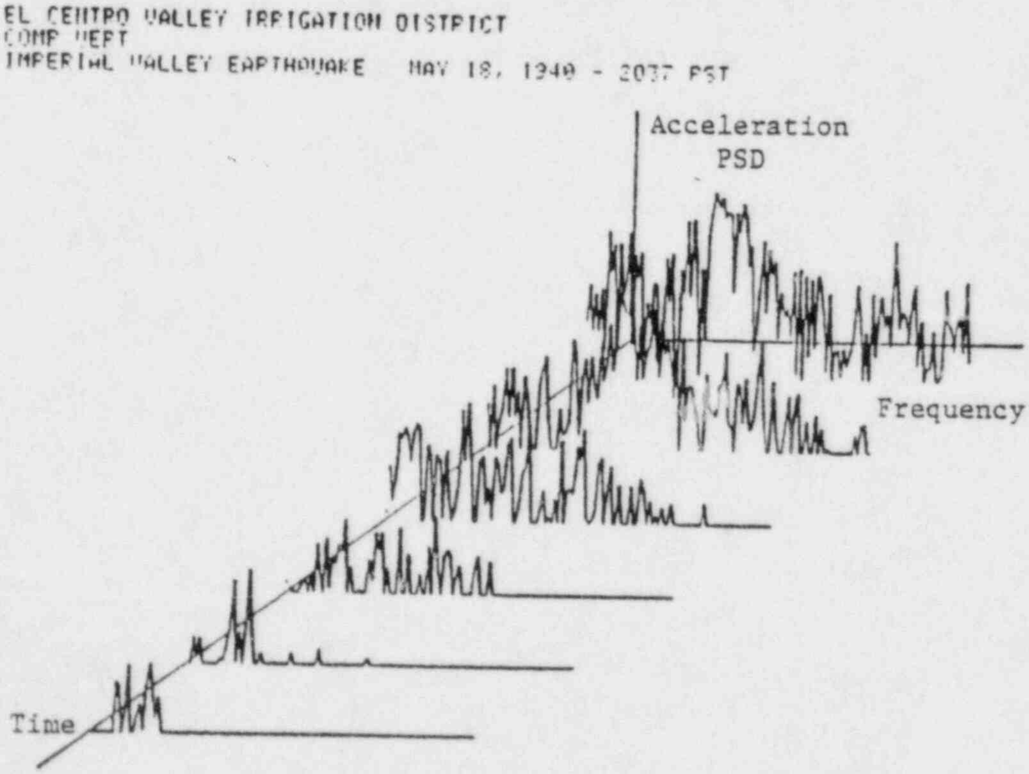


Figure 3.1-6. Time Interval PSD for El Centro 1940 Vertical

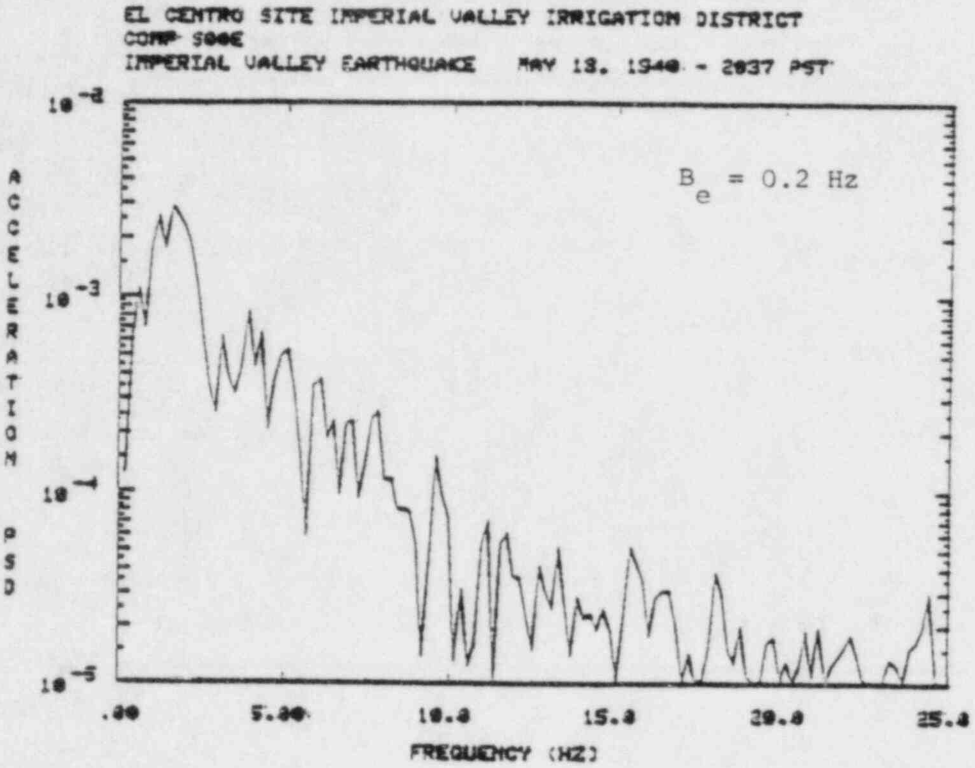


Figure 3.1-7. Computed PSD for El Centro 1940 SM

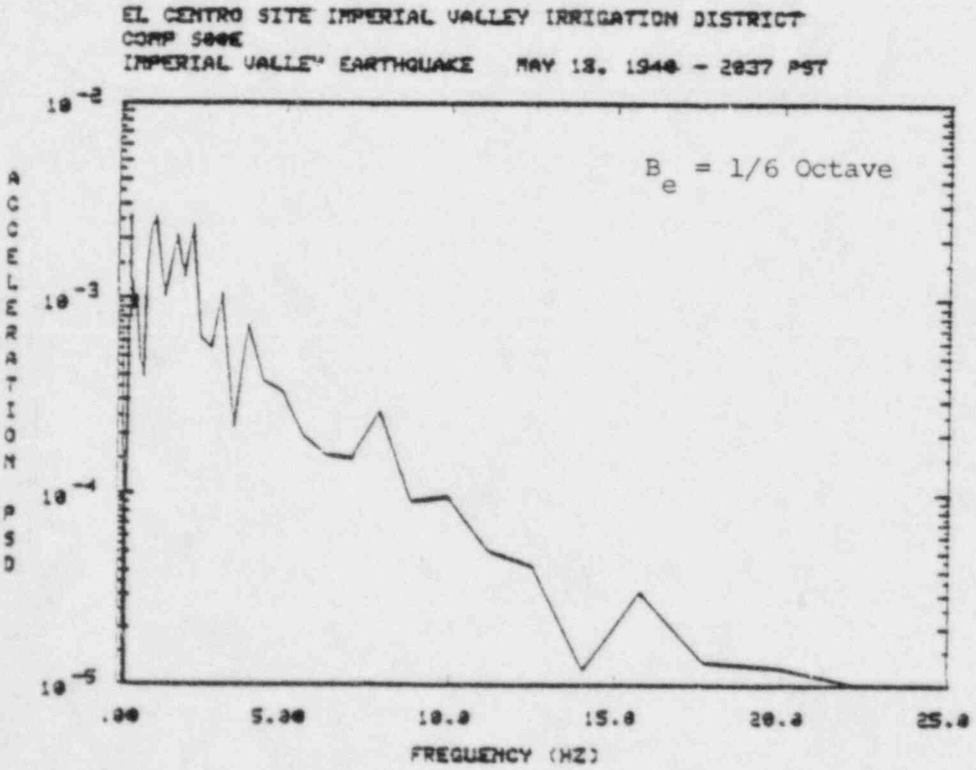


Figure 3.1-8. Transformed PSD for El Centro 1940 SM

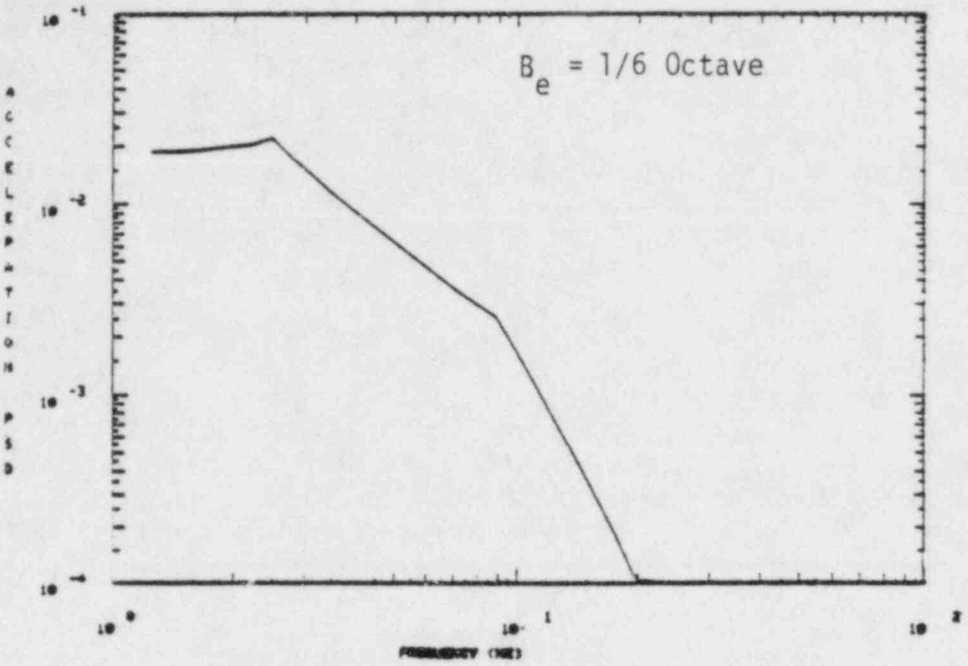


Figure 3.1-9. Transformed NRC Reg. Guide 1.60 RRS at 2% Damping and 1.0 ZPA - Horizontal

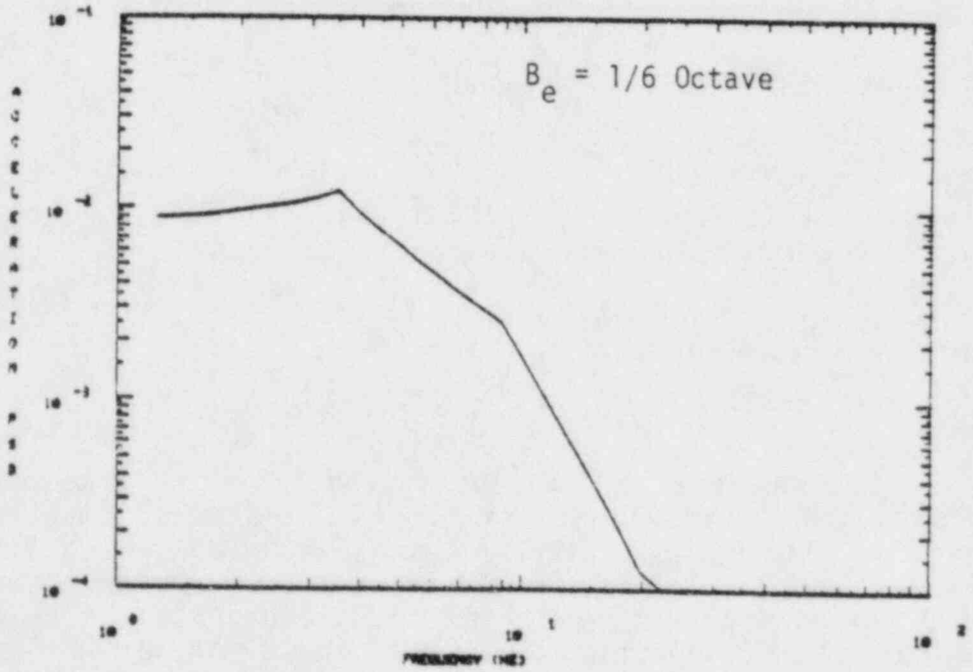


Figure 3.1-10. Transformed NRC Reg. Guide 1.60 RRS at 2% Damping and 1.0 ZPA - Vertical

Figures 3.1-11 and 3.1-12 show the SM data for two El Centro components as analyzed for time interval PSDs in 5.12 second blocks with 0.78 Hz resolution. In each figure the center curve represents the average acceleration PSD, $G_0(f)$, over the entire strong motion portion of the earthquake signal. The upper and lower curves represent an envelope of the maximum, $G(f)_{max}$, and minimum, $G(f)_{min}$, time average acceleration PSD that occurred in any time interval. Thus, a fluctuation band for the time interval PSD's was established for each earthquake component studied.

A comparison of the earthquake measured PSD fluctuations now had to be compared with that of a typical stationary random signal. For this, a two step process was utilized. Ratios of the frequency averaged values G_{max} and G_{min} to the frequency averaged complete strong motion acceleration PSD, G_0, were first plotted as a function of a newly-defined nonstationarity number. Results for all earthquakes components are shown in Figure 3.1-13. The nonstationarity number is defined as

$$N_n = (\bar{a}_{max}/\bar{a}_{min}) \div \bar{a}_{SM} \qquad (3\text{-}2)$$

where $\bar{a}_{max}$ is the maximum time interval RMS acceleration during the strong motion, $\bar{a}_{min}$ is the minimum time interval RMS acceleration during the strong motion, and $\bar{a}_{SM}$ is the average RMS acceleration over the entire strong motion. The larger this number is, the more nonstationary is the data.

In Figure 3.1-13 the upper plotted points represent

$$G_{max}/G_0$$

and the lower plotted points represent

$$G_{min}/G_0.$$

In addition, the shaded vertical bands indicate the extent of 1 standard deviation, and the clear vertical bands indicate extreme values encountered in the data for any time interval. From a statistical point of view, all data is plotted for the same number of sample averages equal to

$$N_s = B_e T_B = 0.78\ (5.12) = 4 \qquad (3\text{-}3)$$

where B_e is the analysis bandwidth and T_B is the time in each block. For the given number of data samples a Chi-squared distribution [3] predicts, with 98% confidence, that all such data will fall within the indicated horizontal lines for a true stationary random process. Thus, for all five earthquakes indicated, the process can be reasonably approximated as being stationary. The data for the Parkfield earthquake was not plotted since its strong motion portion is very short and was not considered a true representation of a far field earthquake acceleration signal. However, it was surmised that most earthquakes of concern are more like the group of five indicated.

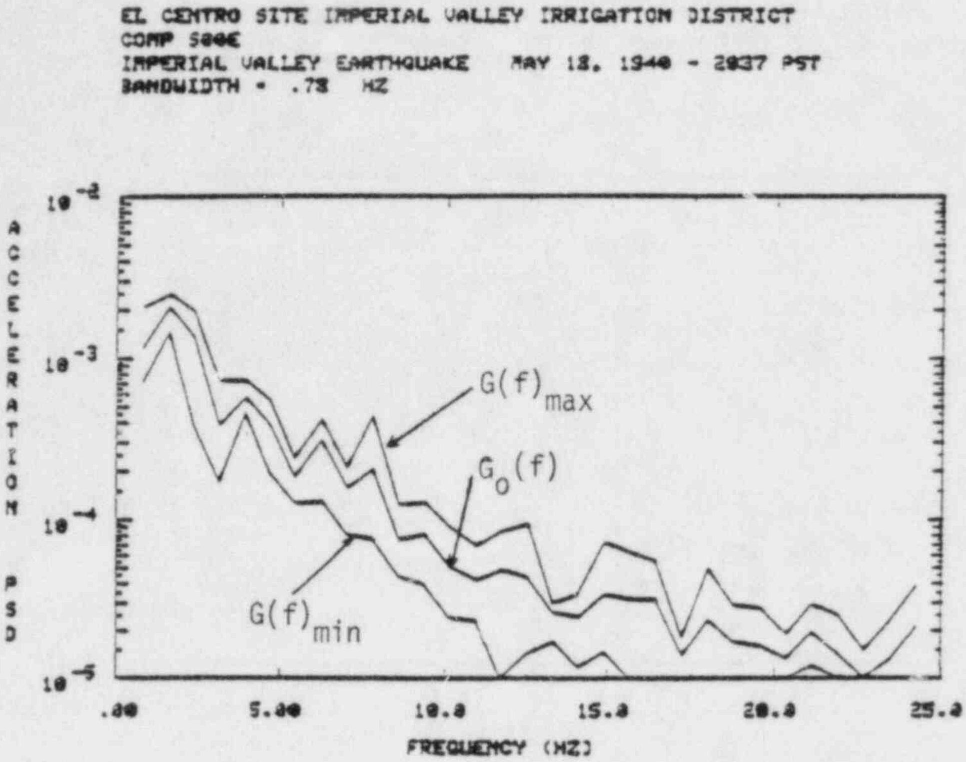


Figure 3.1-11. Frequency Stationarity in El Centro 1940 NS SM

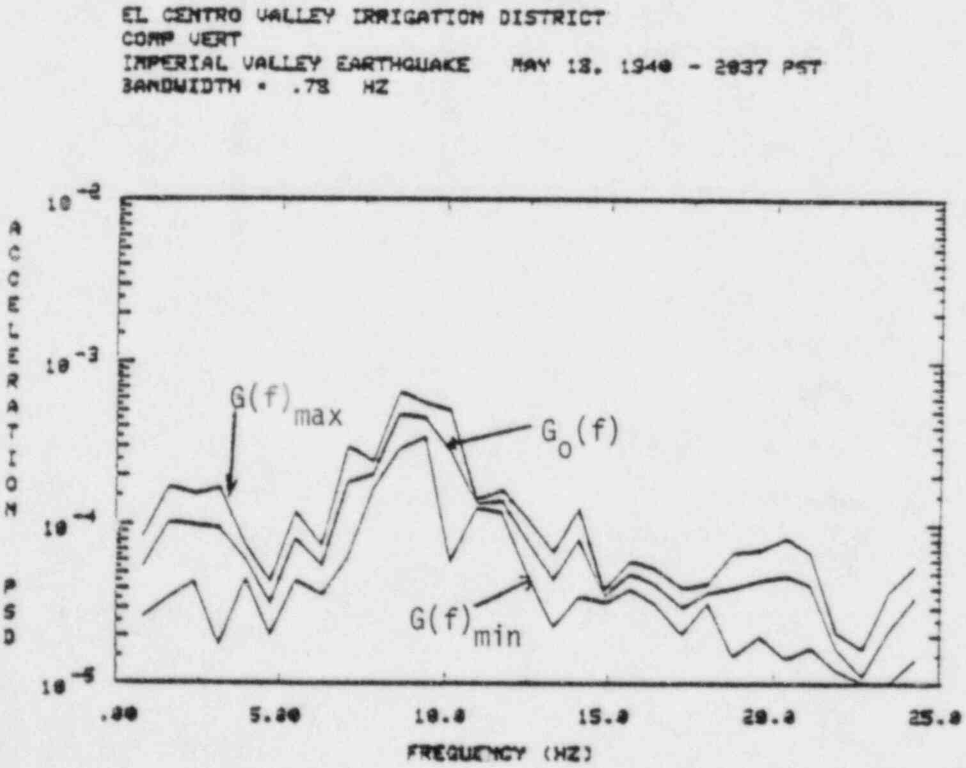


Figure 3.1-12. Frequency Stationarity in El Centro 1940 Vertical SM

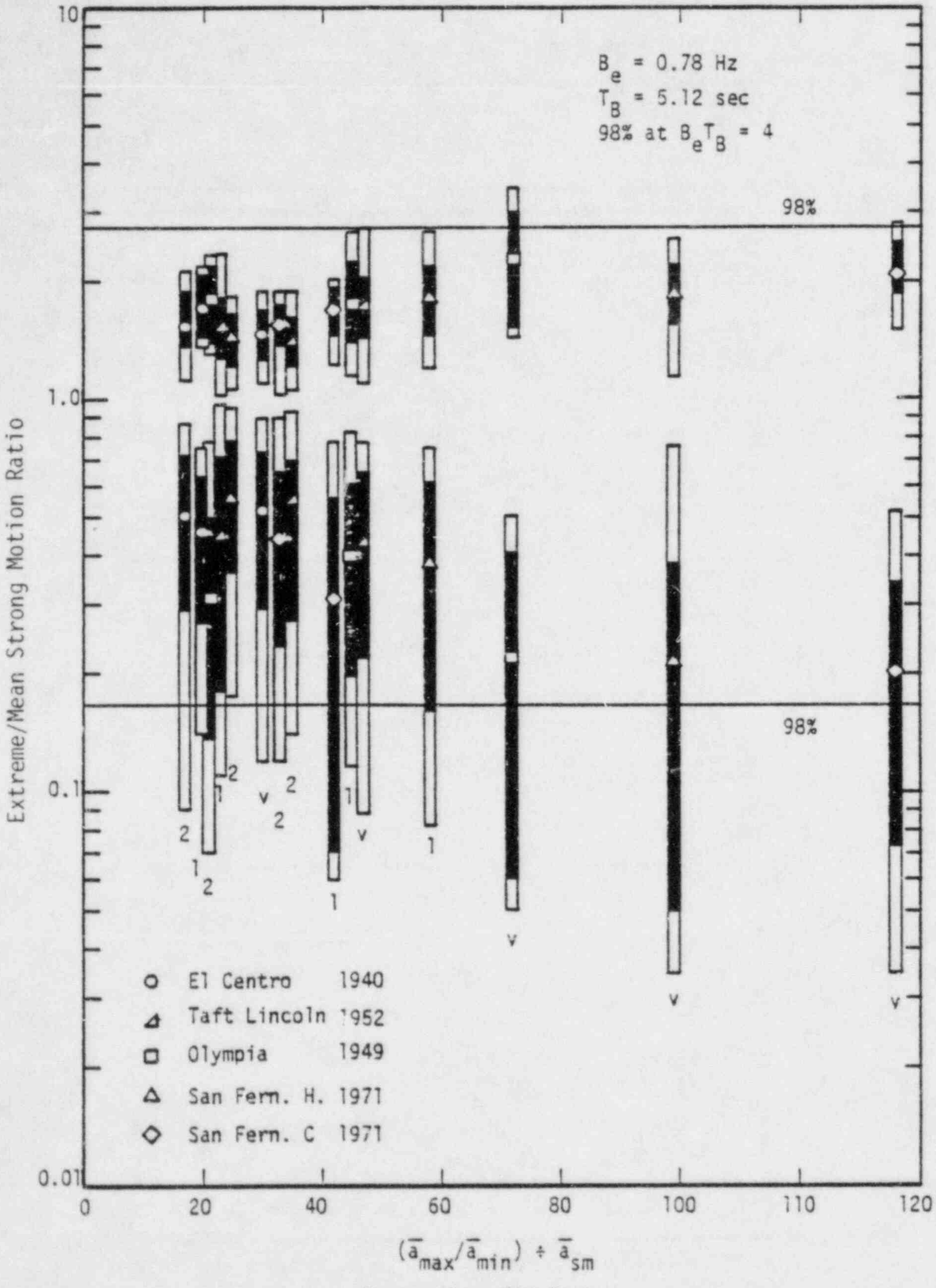


Figure 3.1-13. Frequency Stationarity for Several Earthquake Strong Motions

A further question arises as to what changes result if the time interval and resolution bandwidth combination are changed from $B_eT_B = 4$? Figure 3.1-14 shows what the effect of sample size would be. The curves represent a plot of the confidence lines for a stationary random process as given by the Chi-squared distribution. The average fluctuation ratios for the earthquake PSD's are also plotted at $B_eT_B = 4$. It can be seen that with more data the fluctuation limits should decrease, as indicated. Thus, any candidate test or analysis time history can be analyzed according to time interval PSD and found acceptable if it falls within the 98% bounds of

$$G_{max}/G_o < 2.8 \qquad (3\text{-}4)$$
$$G_{min}/G_o > 0.17$$

The exact bounds are a matter of judgement, of course, where the above members were chosen to be the most liberal possible.

3.1.5 Coherence and Probability Density

Chen [10] has shown that ground level earthquake horizontal components are essentially statistically independent, while the horizontal and vertical components are only slightly dependent. Quantitatively he showed that the horizontal components of earthquakes demonstrate a correlation coefficient (at zero time delay) of about 0.16-0.20. This information itself is sufficient to establish a criteria for the statistical independence of simulated earthquake ground motions. However, the correlation coefficient is a parameter that is not readily calculated with most commercially available laboratory FFT analyzers, while the coherence between two signals is. Furthermore, the coherence is a function of frequency [11], and can readily be used to identify where cross coupling occurs in structural response. Therefore, coherence was chosen as the basis for quantification of appropriate statistical independence.

The coherence of all possible combinations of the strong motion portion of components for each of the six earthquakes was computed. Figures 3.1-15 and 3.1-16 show sample results. It was concluded that for most typical earthquakes a coherence of about 0.5 or less is appropriate for the analysis bandwidth of 0.78 Hz. The Parkfield earthquake, on the other hand showed coherence as high as 0.8 to 0.9. This occurred because of the near proximity of the measurements to the epicenter of the earthquake. Since this is a rather atypical situation, the coherence of 0.5 or less appears to be more appropriate. For this analysis the number of 5.12 second blocks during the strong motion portion of each earthquake component varied from one, for Parkfield, to five, for Olympia. The number of samples in each block, obtained from equation (3-3), remained four, as in previous analysis. Because of short duration of the earthquake signals the normalized random error may be large.

In a similar study Lin [12] looked at the cross correlation, coherence and motion distribution for twenty-two pair of horizontal earthquake signals. From the acceleration time histories he was able to

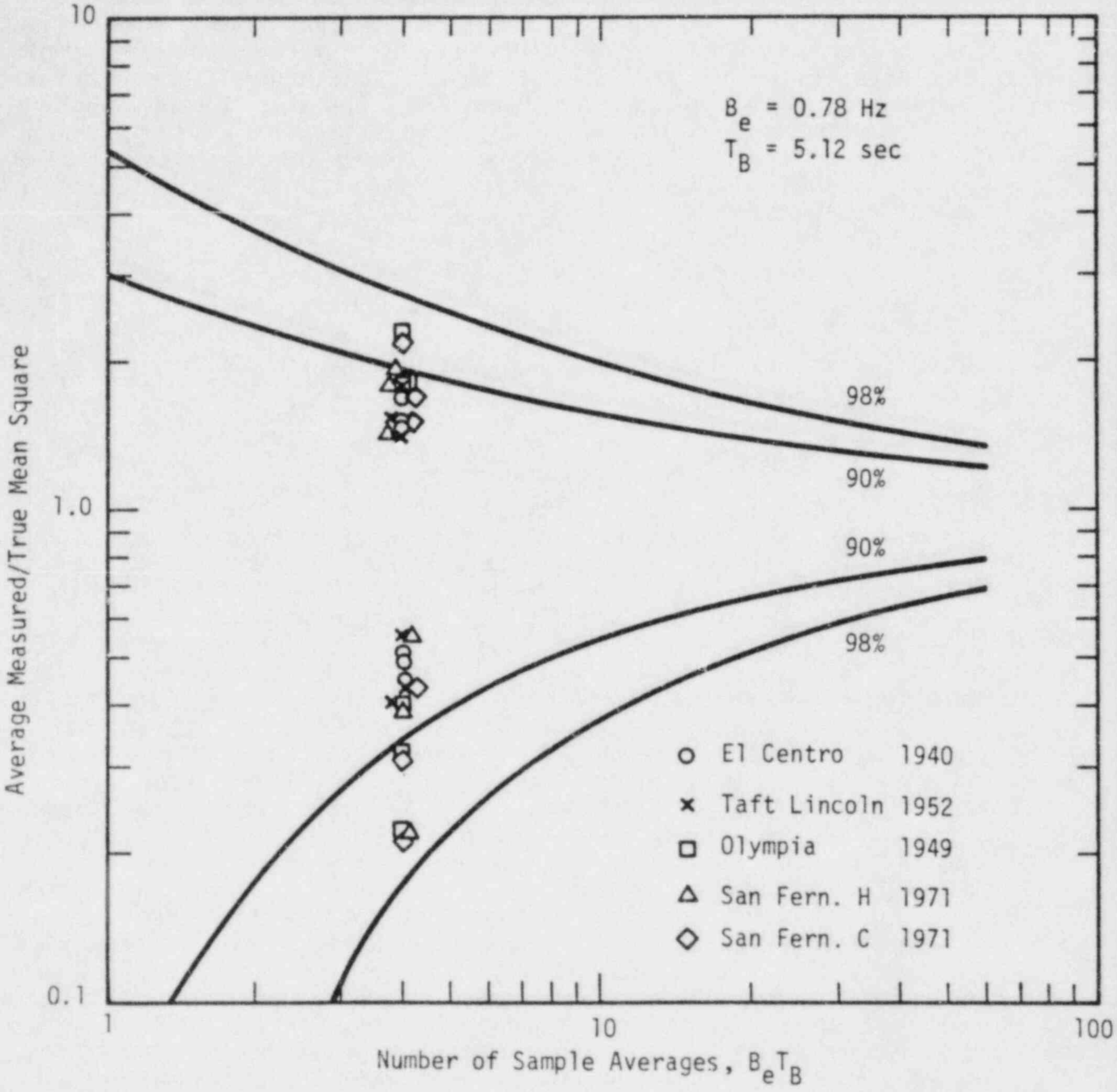


Figure 3.1-14. Effect of Sample Size on Stationarity Measurement

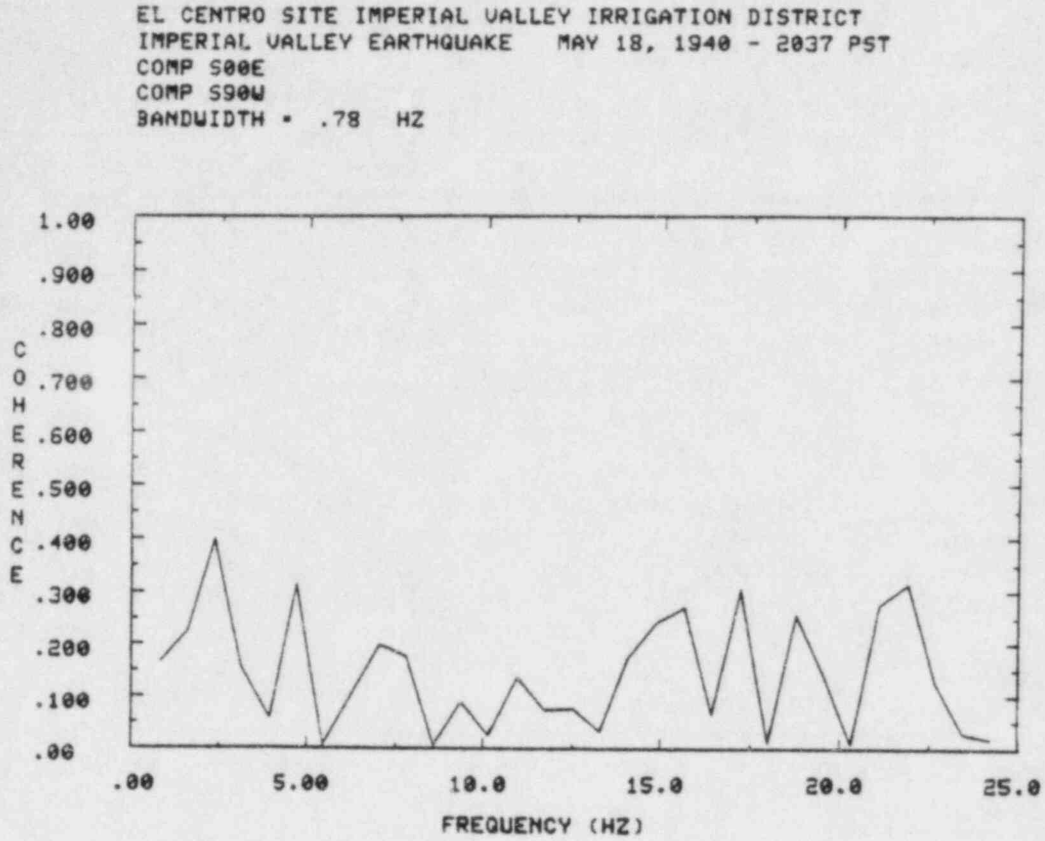


Figure 3.1-15. El Centro 1940 SM NS-EW Coherence

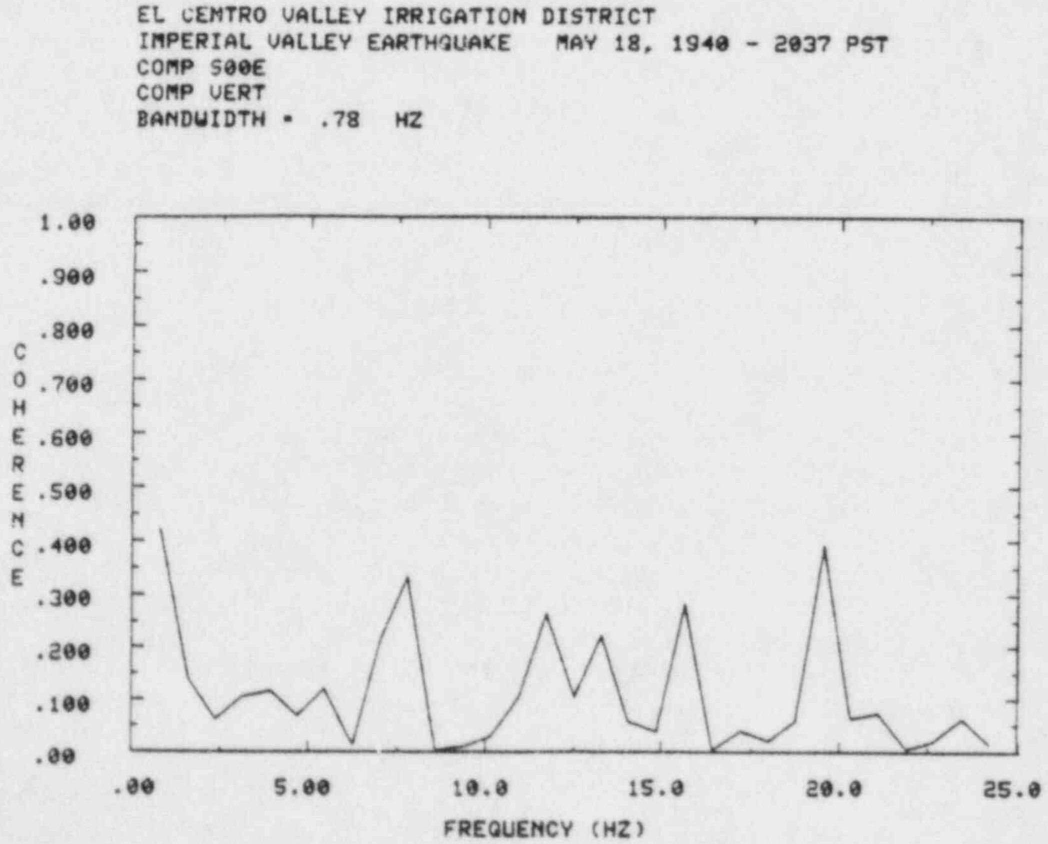


Figure 3.1-16 El Centro 1940 SM NS-Vertical Coherence

obtain the mean and standard deviation values for coherence of the ensemble of earthquakes. By using the ensemble averages at each frequency he was able to reduce the error although his analysis bandwidth was extremely narrow, 0.2 Hz. The results indicate a mean coherence for most frequencies of less than 0.5 for all horizontal components which are similar to the results of this study. In an attempt to present the results on a basis similar to that of Reference [9] Lin also drew an envelope of the mean plus one standard deviation values. The results show coherence at most frequencies of less than 0.80.

Amplitude probability density is another important description of the earthquake motion. It expresses implicitly the percentage of the time that the amplitude is within a given interval during the strong motion. This is obviously important for fatigue and other repeated cycle failure considerations. Typical samples of amplitude probability density for corresponding strong motion portion of components are shown in Figures 3.1-17 and 3.1-18. The results are compared with a standard Gaussian or normal distribution and can be seen to be only approximated by it. In some cases the distribution is more centrally concentrated, so that somewhat higher ratios of peak to RMS may be expected at the same probability level. Thus, a peak acceleration (ZPA) to RMS ratio for the strong motion may be as high as 4.0 to 6.0.

3.1.6 Statistical Analyses Parameters

Resolution bandwidth B_e, number of data samples per block, B_eT_B, statistical degrees of freedom DOF, etc., are all statistical analysis parameters that are listed on the various preceding figures. These parameters describe the degree of statistical accuracy that can be expected from a stationary random process. For a long duration stationary random process, it is customary to utilize large (i.e., 50-100) sample averages, N_s, or degrees of freedom, DOF, for estimating the various parameters. This corresponds, for each block, to

$$N_s = B_eT_B \text{ or } DOF = 2B_eT_B \qquad (3\text{-}5)$$

as was mentioned before. However, the strong motion portion of earthquakes is typically relatively short in duration. With a resolution bandwidth of about 1 Hz (a reasonable value for lightly damped structures), it is apparent that relatively low numbers of sample averages must be contended with. Nevertheless, for each presentation of such data, it is important to state what the analysis parameters are so that the appropriate statistical variation of the results can be kept in perspective. For example, the coherence functions in Figures 3.1-15 and 3.1-16 are computed with 0.78 Hz resolution and 24 DOF (12 Sample Averages). A smaller portion of the data analyzed would show higher coherence variations. Similarly, the amount of spread expected on PSD's as a function of sample averages is shown in Figure 3.1-14. Thus, in stating any criteria the statistical accuracy must be borne in mind where appropriate. General texts on the analysis of random data, [11] for example, give the procedures used to calculate the bias and random errors for a number of statistical quantities.

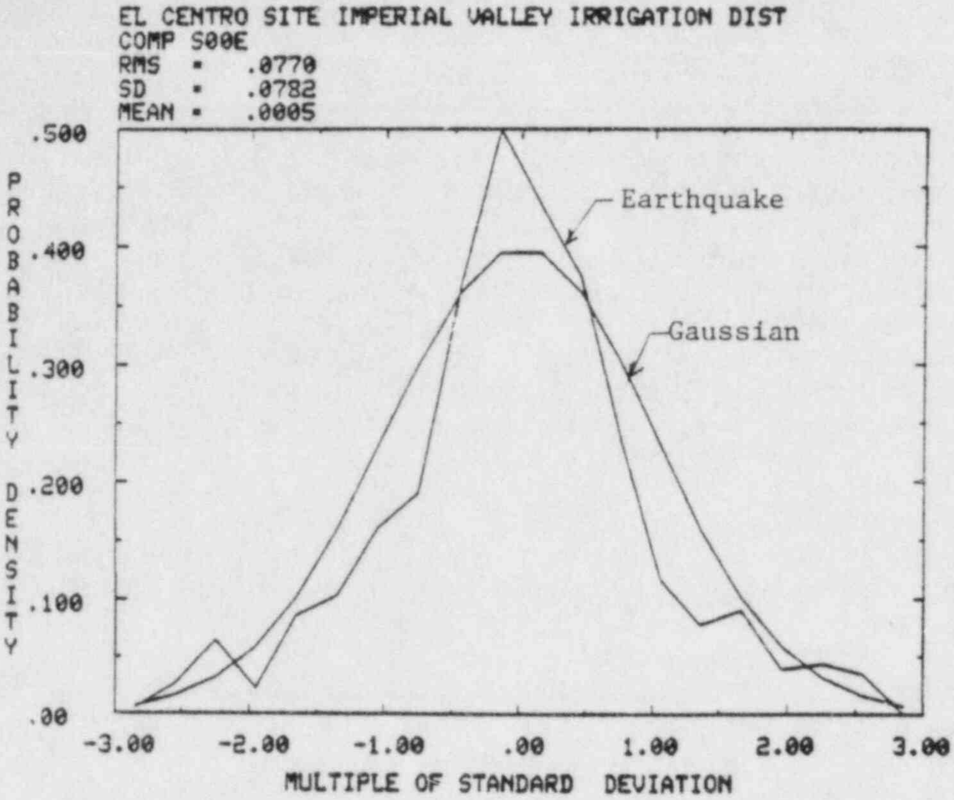


Figure 3.1-17. El Centro 1940 SM NS Probability Density

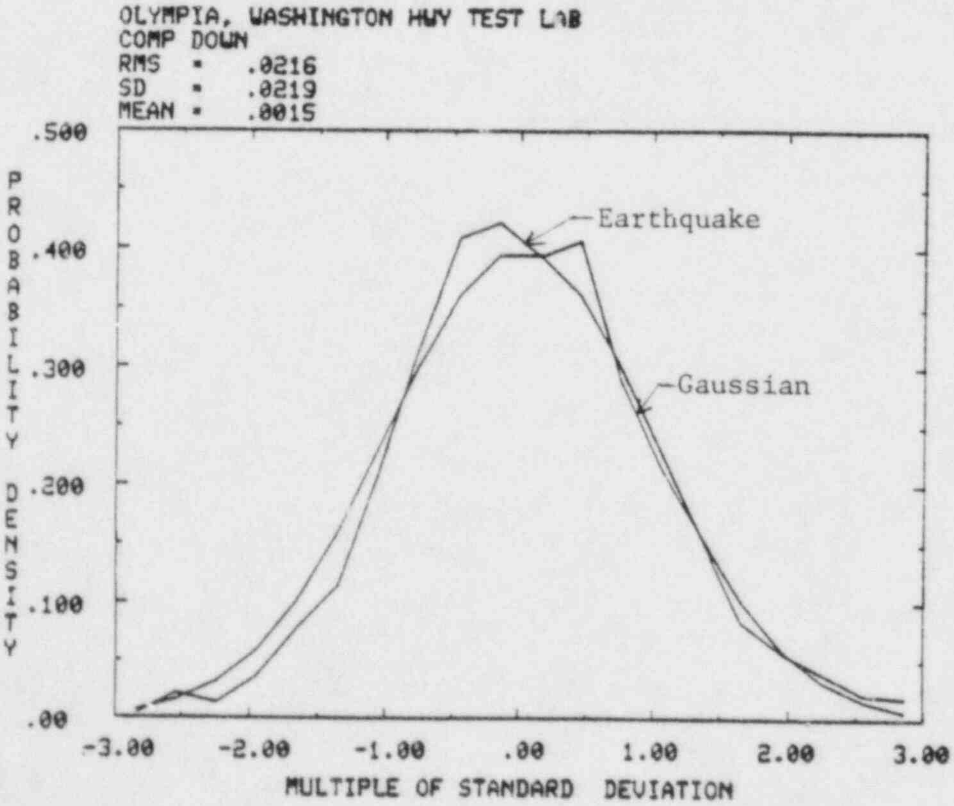


Figure 3.1-18. Olympia 1949 SM Vertical Probability Density

3.2 Floor Level Simulation

The preceding data indicates that the strong motion portion of typical earthquakes at ground level can be simulated by a stationary random process having approximately a Gaussian amplitude probability density and a decreasing PSD between 1 and 33 Hz. Furthermore, the three components are relatively independent, having a coherence of 0.5 or less. It now becomes appropriate to consider what this motion becomes at the various floor levels of buildings. In view of the above random excitation characteristics, several general statements can be made about motion responses at floor levels, assuming that the building can be represented by a system having a linear transfer function between the base excitation point and the floor level response point [3,11].

The response motion at the floor level of a building can be predicted by Equations (2-1) through (2-4), or by using time history solutions. However, in view of the stationary random character of the strong motion portion of excitation, Equation (2-4) is especially appropriate. Thus, the PSD at a floor level will also be a stationary random signal, and will also be approximately Gaussian in amplitude distribution, similar to the excitation. Frequency content is determined from that of the excitation PSD and the building transfer function according to Equation (2-4). Coherence between orthogonal axis motions at the floor level may no longer be low at all frequencies. In particular, in some parts of the frequency range, coherence between two horizontal directions may be very high, where torsional modes of the building occur. Furthermore, coherence between horizontal and vertical may be high where modes involve off center mass coupling. Thus, floor level motions will generally also be uncorrelated, except for narrow frequency ranges where coupled building modes occur.

4.0 ELECTRICAL RACK SPECIMEN

The selection of a test specimen was dictated by several restraints. One was that it be representative of one of the generic groups given in Reference [1]. The group selected was electrical equipment mounts which includes panels, racks and cabinets. This group is important because its structural nature allows for the development of analytical models of the structure which may be used alone or in conjunction with testing for qualification. On the other hand the components mounted on these racks are difficult to model and therefore are either tested in the assembly or as individual components using response spectra defined at the instrument location. It was hoped that by testing this type of specimen, information on analytical procedures, in-situ testing, and equipment qualification testing could be obtained. Once the generic subgroup was selected several additional requirements had to be satisfied. Both operational equipment (for functional checks) and lumped mass dummy equipment (to look at instrument simulation) was desired. To study the influence of coupling the mass and stiffness had to be nonsymmetrical. Finally, blueprints or drawings had to be available from which to develop the Finite Element Model (FEM). It was felt that it would be more representative of current practice to develop the model from drawings rather than physical measurements on the test item.

A second major restraint was to demonstrate which types of test waveforms are applicable to which generic groups. Equipment qualification testing has included sine sweep, sine dwell, decaying sine, sine beat, narrow band random, wide band random, complex analog, and complex digital signals. The broad frequency testing is more representative of the earthquake signal for most situations. For equipment, such as valves, whose supports act as filters of earthquake signals the narrow frequency band tests may be more realistic. Testing of an electrical equipment mount would be concentrated in the broad band testing. Future tests are planned on a valve to look at the alternative condition.

4.1 Description of Rack and Instrumentation

The 48-inch local instrument rack is a welded steel structure weighing approximately 725 pounds with instruments, but excluding the baseplate. Overall dimensions are 48" wide, 30" deep and 94" high. The rack is made up of four major components; baseplate, major frame members and bracing, instrument rack and instruments, Figure 4.1-1. For mounting purposes, the framework was centrally placed and welded to a 4 ft x 4-1/2 ft x 1 in. thick steel plate which was drilled for mounting on the SwRI seismic simulator. The welding pattern consisted of 1/4" x 1" skip welds spaced every 12 inches on the 48-inch sides (front and back), and every 10 inches on the 30-inch sides (ends) of the rack. The pattern was initiated from the corners on each side.

Major structural members were 2-1/2 x 2-1/2 x 1/4 steel angle welded together to form the rectangular frame, Figure 4.1-2. These were then braced horizontally and diagonally on each side, using 2 x 2 x 1/4 angle, to stiffen the structure in the fore-aft direction, X axes. The

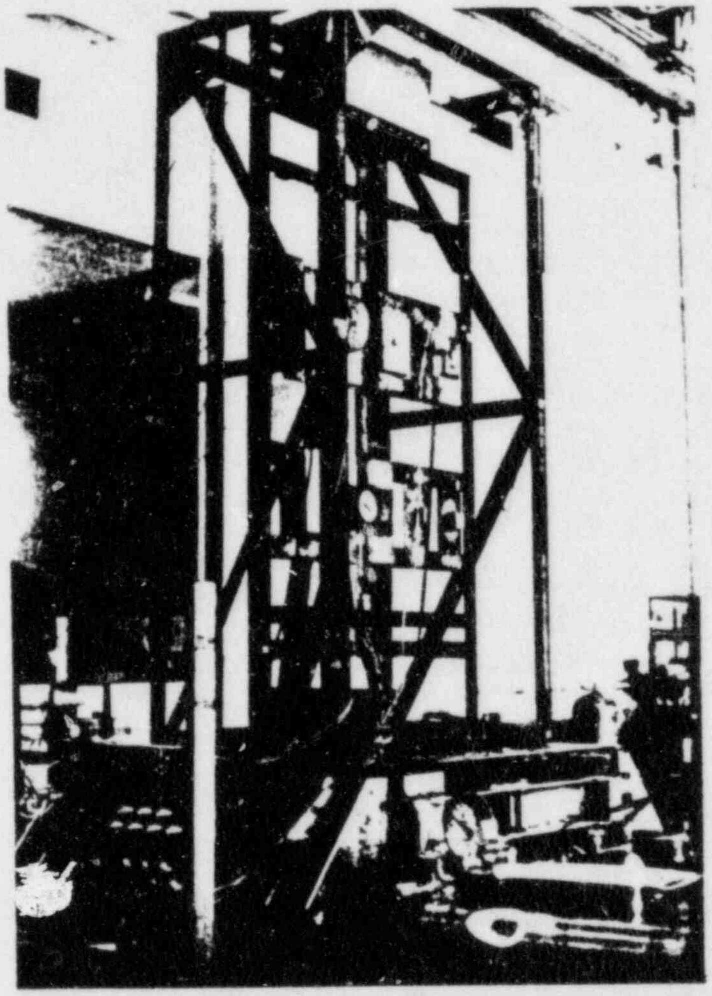


Figure 4.1-1. Electrical Rack Mounted on Seismic Simulator

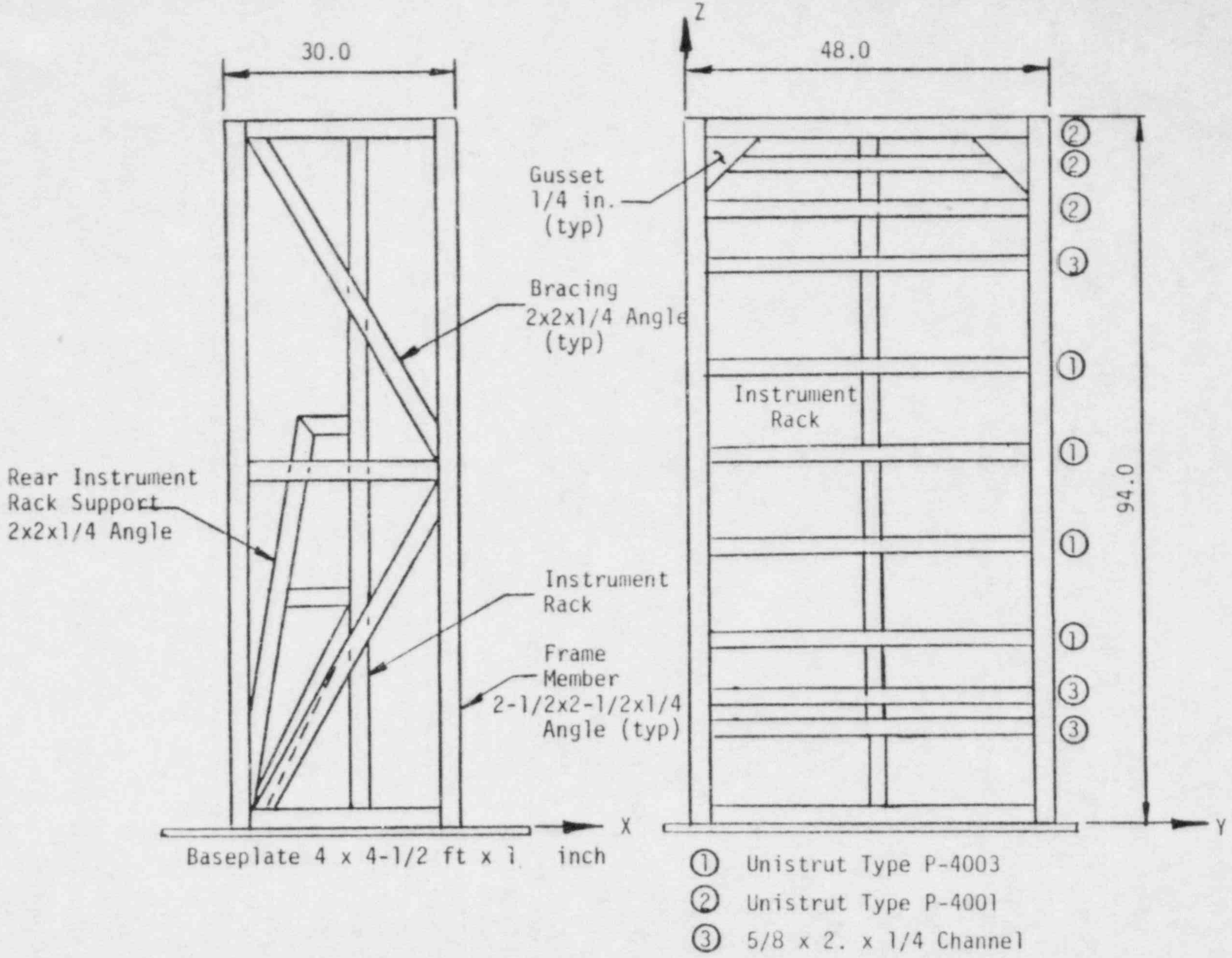


Figure 4.1-2. Electrical Rack Structure and Axes

only stiffeners in the side-to-side direction, Y axes, were the gussets at the top of the frame. An additional brace was used to stiffen the instrument rack in the X-axes direction and is located in the center back of the panel. It is tied to the instrument rack at elevations 32.0 and 55.0 and to the base at the rear.

The instrument rack consists of three vertical members and ten horizontal members on which the instruments are mounted. The side vertical members were welded to the top and bottom rectangles and the bracing. Horizontal members were then welded to side angles and support the center vertical member. This 2 x 2 x 1/4 channel ran from the top UNISTRUT to the bottom channel, not all the way to the baseplate. There were three different types of horizontal members: UNISTRUT Type P-4003, UNISTRUT Type P-4001 and 5/8 x 2 x 1/4 channel.

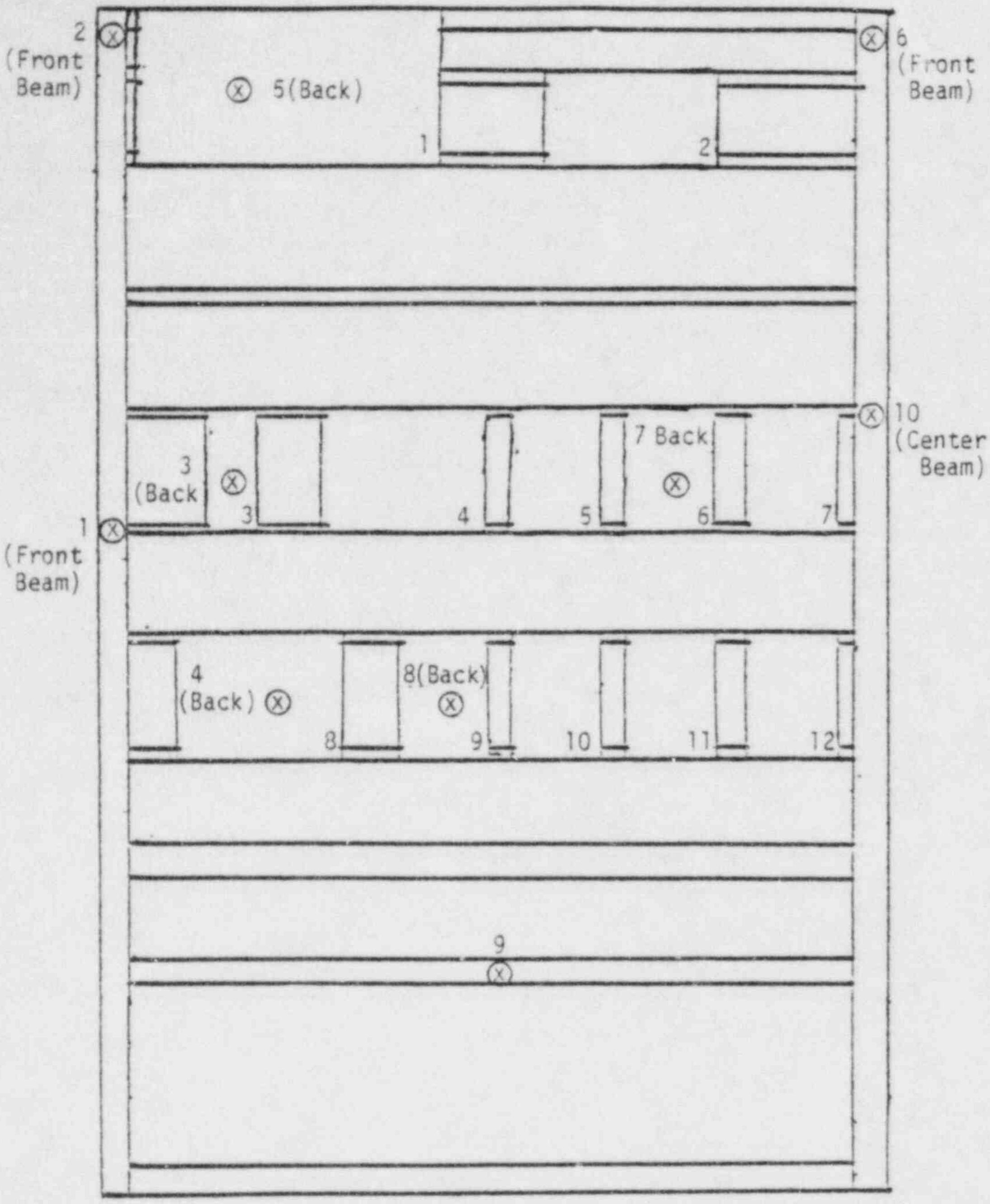
Both operational and dummy mass instrumentation were used on the instrument rack, Figure 4.1-3. The two NEMA boxes were sheet metal enclosures attached to the UNISTRUT's at their corners. Additional mass was attached to the back of each box to simulate internal components. The four operational instruments were:

1) Yarway 4418C Level Indicator/Switch
2) Barksdale D2H-M80SS Pressure Switch
3) Rosemount 535E Temperature Transmitter
4) Robertshaw SP-222-C Pressure Switch

The Yarway is designed to sense fluid levels and trip when the level exceeds or goes below a preset value. Typical applications include control of the reactor recirculation pumps used to supply cooling water to the reactor. Monitoring of pressures such as turbine inlet and exhaust levels and pump suction and discharge pressures are typical applications of the Barksdale and Robertshaw pressure switches. Temperature transmitters, such as the Rosemount, are used in the monitoring circuit used to sense and display information on temperatures throughout the nuclear power plant. Each of these instruments are typical of Class 1E components which require qualification to insure functionality before, during and after the postulated seismic event. These four instruments were placed at the locations shown in Figure 4.1-3. Each was attached to a support plate, 1/8 inch thick, which was in turn attached to the UNISTRUT members using the supplied hardware.

Dummy masses were placed at the other six instrument locations. These mases were bolted to support plates which were in turn attached to the UNISTRUT members. The sizes of the masses and support plates are given in Table 4-1. The size of the dummy weights were chosen to realistically simulate actual instrument weights. Additional masses were added to the instrument rack to simulate electrical, pressure and fluid connections. A total of twenty-eight 1.5 pound blocks, six 2.5 pound blocks and six 3.0 pound blocks were distributed over the rack.

During testing the four operational test items were supplied with known electrical power and pressures so that their functionality could be checked. The Yarway, a differential gage, was supplied with 1000 psi absolute water pressure and a specified differential pressure. The trip



1. NEMA Box (Large)
2. NEMA Box (Small)
3. Yarway 4418C Level Indicator Switch
4. Dummy Instrument
5. Dummy Instrument
6. Barksdale D2H-M80SS
7. Dummy Instrument
8. Rosemount 535E
9. Robertshaw SP-222-C
10. Dummy Instrument
11. Dummy Instrument
12. Dummy Instrument

⊗ Accelerometer Locations

Figure 4.1-3. Instrument Arrangement for 48" Rack

TABLE 4-1. INSTRUMENT AND DUMMY WEIGHTS

Instrument Number	Weight (lbs)	Support Plate Size (in)	Support Plate Weight (lbs)	Total Weight (lbs)
1	41.7	---	---	41.7
2	13.0	---	---	13.0
3	29.5	16 x 4 x 0.125	2.3	31.8
4	22.7	14 x 8 x 0.125	4.0	26.7
5	7.8	14 x 6 x 0.125	3.0	10.8
6	1.8	14 x 6 x 0.125	3.0	4.8
7	3.2	14 x 6 x 0.125	3.0	6.2
8	10.7	14 x 8 x 0.125	4.0	14.7
9	1.5	14 x 6 x 0.125	3.0	4.5
10	3.1	14 x 6 x 0.125	3.0	6.1
11	1.9	14 x 6 x 0.125	3.0	4.9
12	2.2	14 x 6 x 0.125	3.0	5.2

point was set at 5.0 psi differential. To check functionality the electrical contact of the trip mechanism was monitored using a DC voltage. Chatter or tripping would be noted by a change on state 0.0 to 1.5 Vdc for normally open contacts or 1.5 to 0.0 Vdc for normally closed contacts. For these tests, failure was defined as the first indication of chatter. The instrumentation was able to indicate chatter of more than two milliseconds duration. It is important to remember that these experiments were performed to investigate test procedures, and not actually to qualify the equipment. The definition of failure, operating conditions, and levels of excitation were set at the time of testing to obtain the required information. The Barksdale pressure switch is designed for low absolute pressures. The trip point was set at 10.0 psi absolute water-pressure with test runs made at a specified pressure. The electrical contacts were again monitored using a DC power supply. For functional checks of the Rosemount temperature transmitter a known voltage was supplied to the input, simulating a thermocouple, and the output current monitored. The current was measured using a digital multimeter and also monitored on an oscillograph by measuring the voltage across a known resistor subjected to the output current. Failure of this instrument was defined as a shift in current of more than 10% of full scale reading. The Robertshaw pressure switch is similar in function to the Barksdale except the pressure range is higher. The specified trip point was 500 psi. Functionality was again monitored by noting the state of the electrical contacts of the trip mechanism. All monitoring of the functionality of the devices was performed using an oscillograph. In addition to the functional channels the horizontal and vertical acceleration was also recorded on the oscillograph.

4.2 Tests Performed and Data Acquisition Procedures

A large number of tests were performed on the electrical rack as shown in Table 4-2. These can be divided into two basic groups; structural identification testing and multifrequency table mounted testing. The structural identification testing was designed to obtain information on the natural frequencies, mode shapes, modal masses, and damping of the structure. It included both floor mounted, installation condition, and table mounted, test condition, excitation. Swept sine, broad band random, and impact hammer testing was performed for the floor mounted conditions. The multifrequency table mounted tests included earthquake simulation, sine dwell excitation, sine beat excitation and combined dynamic environment, earthquake and SRV, simulation. Each of these required different setups to monitor and display the required parameters.

4.2.1 Floor Mounted Tests

For the floor mounted studies the one-inch thick baseplate of the electrical rack was bolted to the concrete floor. As was noted during the testing this attachment to the floor can have a significant effect on the frequencies associated with bending and torsion of the frame although local rack modes are not as sensitive. The attachment was made as tight as possible in an attempt to approximate a rigid base for analytical comparison. Excitation was supplied by either a fifty-

TABLE 4-2 SUMMARY OF TESTS ON RACK

- I. Initial Structural Identification (Transfer Functions - 10 Positions)
  - A. Floor Mounted
    - 1. Sine Sweep (25 lb Force pk F-R, 2.5 lb Force pk S-S)
    - 2. Random Excitation (3.5 min., 0.3 Hz BW, 25 lb RMS F-R, 2.5 lb RMS S-S)
    - 3. Impact Hammer (5 Samples each Pos., 0.3 Hz BW)
  - B. Table Mounted
    - 1. Table Fixed at Corners
      - a. Sine Sweep (0.1 g pk)
      - b. Random Excitation (3.5 min., 0.12 g rms)
    - 2. Table Free
      - a. Sine Sweep (0.1 g pk)
      - b. Random Excitation (3.5 min., 0.12 g rms)
- II. Multifrequency Table Mounted
  - A. Earthquake
    - 1. R.G. 1.60 (1.0 g & 2.0 g ZPA)
    - 2. Extended R.G. 1.60 (1.0 g & 2.0 g ZPA, 10-20 Hz added)
    - 3. R.G. 1.60 (10% Match of TRS over RRS)
    - 4. Extended R.G 1.60 (10% Match of TRS over RRS)
    - 5. R.G. 1.60 (Excess Low Frequency & Deficient High Frequency)
    - 6. Extended R.G. 1.60 (Excess Low Frequency & Deficient High Frequency)
  - B. Sine Dwells (Misc. 30 sec at & away from Resonance)
    - 1. Uniaxial
    - 2. Biaxial
  - C. Sine Beats (Misc. 30 sec at & away from Resonance)
    - 1. Biaxial
    - 2. Pauses of 0.5X, 2.0X, and 5.0X Beat Period
  - D. Combined Dynamic Environment
    - 1. SRV Only (2.0 & 5.0 sec, 30-60 Hz BW)
    - 2. Earthquake Only
    - 3. Earthquake plus SRV
- III. Detailed Structural Identification (Modal Analysis - 50 Positions)
  - A. Floor Mounted
    - 1. Impact Hammer (5 Samples each Position, 0.3 Hz BW)

pound electromagnetic (EM) shaker or an impact hammer. The EM shaker was attached to the frame at elevation 47.5 on the front left vertical member (Accelerometer Location 1 on Figure 4.1-3). A massive steel structure was used to support the shaker and act as a reaction mass. For fixed base excitation the input motion had to be controlled by the force level if the transfer functions were to be defined using response accelerations. A force gage was mounted in the connecting rod between the EM shaker and the test item. All responses were measured using an accelerometer. Analysis performed on the floor mounted test item was done in real time with no data recorded for future analysis.

The swept sine testing was performed using a constant level force input swept at a rate of 0.5 octaves/minutes, except near resonances where the rate was decreased. A closed loop control system was used to monitor and adjust the input as the frequency was swept from 1.0 to 100 Hz. Force levels were maintained at 25.0 lbs for fore-aft excitation or 2.5 lbs for side-to-side excitation. The acceleration responses at various locations were recorded on an X-Y plotter in the form of transfer functions. Mesurements were made for both along axes, for example, X-axis excitation and X-axis response, and coupled, for example, X-axes excitation and Y-axis response, motion in an attempt to define system parameters. (Note: Refer to Sections 5.2 and 6.1 for a summary of the results.) At resonance frequencies measurements were made of the damping of the structure using the log decay method. The structure was excited at its resonance frequency to the same levels as the swept sine testing and the power to the shaker turned off. The resulting time history was recorded and the damping obtained using:

$$\beta_r = \frac{1}{2\pi n} \ell n \frac{A_n}{A_o} \qquad (4\text{-}1)$$

where n = the number of cycles
A_o = initial amplitude
A_n = amplitude of the nth cycle.

The results are summarized in Section 5.2.

Random excitation consisted of a low-pass filtered Gaussian noise source fed into the system controller. The input level was adjusted so that the rms value of force, determined using a Nicolet 444A FFT analyzer, was approximately 25.0 lbs_{rms} for fore-aft excitation or 2.5 lbs_{rms} for side-to-side excitation. These levels produced a response of the structure similar to the swept sine levels. The data from the random testing was analyzed using a ZONIC Modal Analyzer. Results were obtained in the form of PSD's of the input force and the response acceleration as well as the amplitude and phase averaged transfer function of these two signals at a bandwidth of 0.31 Hz. Fifty samples of 1024 data points were averaged to obtain the results. Samples of the results are presented in Section 6.1. As in the case for swept sine testing, measurements were made at a number of locations for excitation in the X and Y direction at Location 1, Figure 4.1-3.

The last set of floor mounted tests consisted of impact hammer testing. Results were obtained using the ZONIC Modal Analysis system with excitation provided by an instrumented hammer and acceleration measurements made at various points. Three sets of tests were performed: one set near the beginning of all testing, defined as initial structural identification; one set after the table mounted testing, defined as detailed structural identification; and a final set, defined as mounting condition study. The initial set of tests consisted of two parts, modal frequency determination and mode shape determination. A half pound hammer with an extremely soft head was used to provide excitation to the specimen. The problem in impact testing is insuring that there is adequate energy in the low frequency regime, below 10 Hz. Increasing the weight of the hammer or decreasing the stiffness of the head will increase the content of low frequency excitation. For the hammer used, the largest extender, most mass, was used with additional softening of the tip accomplished by attaching foam pads. Testing consisted of impacting and measuring at a number of locations on the frame and instrument rack. A total of five averages was taken at each location and the results presented as the real and imaginary parts of the averaged cross spectra and the amplitude and phase averaged transfer function at a bandwidth of 0.31 Hz. The natural frequencies obtained were then used in subsequent tests to determine the mode shapes. For these tests the response at Location 1 in the two horizontal directions was measured and excitation, using the hammer, applied at a number of locations on the frame and electrical rack. The ZONIC Modal Analysis system is capable of processing the results and determining the mode shapes at predefined frequencies. The results of this testing were then combined with the random and swept sine results and summarized, see Section 5.2.

Additional impact hammer tests were performed after the table mounted testing of the electrical rack. These tests were run to obtain a better definition of the mode shapes, determine the damping and obtain an estimate of the modal masses. As in the previous impact testing, the ZONIC Modal Analysis system was used to process the data. A larger three pound hammer with a very soft head was used for excitation. Significant energy was input into the system from 3 to 100 Hz. For this series of tests the location of excitation was kept constant and the response accelerometer moved, opposite of previous tests. Using the circle curvefit procedures in the ZONIC the damping and modal mass at the specified frequencies were estimated. Results from this series of testing can be found in Sections 5.2 and 6.6

The final series of impact testing was to look at possible variations in natural frequencies and amplitude of the transfer functions due to changes in mounting. Tests were performed for two different rack orientations and two different attachment torques. The results are again summarized in Section 5.2.

4.2.2 Table Mounted Tests

The table mounted testing was performed on the SwRI Seismic Simulator. This facility has the capability of realistic simulation of an earthquake dynamic environment as well as all accepted standard approximations of such an environment. Although it was designed principally for qualification testing of typical components to be used in nuclear and conventional power generation stations it is also particularly suited to the study of structural scale model responses to seismic excitation. It can further be used as a general purpose shaker facility within its range of operation, and therefore can simulate nuclear plant operating transients.

A mounting surface of up to 6 by 6 foot can be excited with simultaneous vertical and horizontal motion that is arbitrary and independent along each axis. Extenders are utilized for mounting somewhat larger specimens, when necessary. Maximum table payload capacity is 6,000 pounds deadweight. Drive mechanisms are servo-controlled electrohydraulic, and having the following capabilities:

	Horizontal	Vertical
Frequency Range	0-250 Hz	0-250 Hz
Force Capacity	10,000 lb	20,000 lb
Maximum Stroke	8.0 in.	7.0 in.
Maximum Velocity	90 in./sec	22 in./sec
Maximum Acceleration*	10 g	10 g

*At zero payload.

Excitation signals are provided typically by function generators or actual seismic signals recorded on analog instrumentation tape. Table displacement is accurately controlled at low to medium frequencies by automatic feedback to respond to an arbitrary voltage signal. Deterioration in control is experienced at higher frequencies such that open-loop operation is necessary in this range. Table responses are monitored by accelerometers whose outputs can be analyzed according to several standard parameters. Acceleration or velocity response spectrum can be computed and plotted using a Spectral Dynamics SD321 Shock Spectrum Analyzer, or by a DEC PDP 11/70 computer system. Power spectral density, probability density and other associated statistical parameters can also be computed. All time histories can be recorded on analog or digital tape, on oscillographs, or monitored on oscilloscopes. Large volumes of data are usually recorded first on analog tape and then digitized for processing through a digital system which includes a DEC PDP 11/70 computer as its central processor.

The first series of table mounted testing consisted of some additional structural identification testing. With the electrical rack mounted on the seismic simulator, Figure 4.1-1, resonances searches were performed for X, Y and Z axis base input motion. Excitation was either swept sine or broad band random with input levels of 0.1 g peak and 0.12 g rms respectively. Results are in the form of transfer functions for both sets of data, see Section 6.1. Two different table configurations were used for the horizontal test. The table has fixtures so that it can be fixed at the corners allowing for only horizontal excitation. This configuration most closely approximates a fixed base condition with only the stiffness of the table top coming into play. The other condition is with the table free and centered for both horizontal and vertical excitation. This is the test condition and the additional compliance of the hydraulics and vertical table mechanism are present. The two types of signals and two table configurations were run to determine the influence they might have on the results.

The primary objective of the test program was to subject the table mounted electrical rack to a number of test waveforms. These were to include simulated earthquake events, sine dwells, sine beats and combined dynamic environment simulation. Each one of these has been or is currently being used for the qualification of equipment.

All earthquake simulation was based on the Required Response Spectrum, RRS, defined in R.G. 1.60. The earthquake signals were generated on a digital system developed at SwRI. The digital control system on SwRI's seismic simulator is an open loop system with the operator in direct control. The input drive signal adjustment is based directly on the match of Test Response Spectrum, TRS, to the RRS. The exciter displacement drive signal is generated from the linear sum of a series of 1/6 octave psuedo random noise signals. The signals are generated in the time domain as:

$$F_i(t_k) = W(t_k)\,\overline{F}_i(t_k) \qquad i = 1 \text{ to } 34 \tag{4-2}$$

where

$$\overline{F}_i(t_k) = \sum_{j=1}^{20} \cos\,[2\pi\, f_{ij}\, t + \theta_j] \tag{4-3}$$

f_{ij} are the uniformly distributed frequencies in the ith 1/6 octave band, θ_j are the uniform random distribution of phases, t_k is a time variable discretized at a fixed sampling rate, and $W(t_k)$ is the build-hold-decay weighting function (5-15-10). For the most part, each of the generated signals appear to be nonstationary narrow band random. The drive signal for a single axis is then obtained by a weighted sum of the individual 1/6 octave band signals,

$$X_D(t_k) = \sum_{i=1}^{NB} \alpha_i\, F_i(t_k) \tag{4-4}$$

where the α_i's are the weighting coefficients and NB is the number of bands for which signal energy is to be input. A total of thirty-four 1/6 octave bands are available from 1 to 50 Hz to cover the range typically associated with earthquake excitation 1 to 33 Hz.

In order to obtain an initial estimate of the weighting coefficients for a given drive signal, an estimate of the system transfer function is obtained from a data bank stored on the computer. Through the use of the data bank of transfer functions an initial estimate of the table response is made and a time history generated. A TRS is generated from the time history and compared to the RRS and the "α" coefficients adjusted. This process is repeated until a satisfactory matching is obtained. The α-weighting coefficients are then stored for future use during actual item excitation. The drive signal for the second axis is then independently shaped in an identical manner.

The algorithm for adjusting the α-weighting coefficients is based directly on the match of the TRS to the RRS. At the onset of the signal shaping operation the test operator selects desirable tolerances by which the TRS must match the RRS by specifying a lower limit (AMIN) and an upper limit (BMAX). For the ith 1/6 octave band, if

$$RRS_i * AMIN \leq TRS_i \leq RRS_i * BMAX \qquad (4\text{-}5)$$

then no adjustment in the corresponding α_i is necessary. However, if Equation (4-5) is not satisfied, an adjustment of the form

$$\alpha_i = ((BMAX + AMIN)/2) * (RRS_i/TRS_i) * \alpha_i \qquad (4\text{-}6)$$

is made to generate α_i, a modified weighting coefficient for that band. The initial shaping operation is accomplished totally with software resident in the DEC PDP 11/70 and 11/23 network.

With preliminary signal shaping completed the test item is mounted on the table and excited with the initial drive signals which may, at the option of the test operator, be reduced to 1/2 to 1/4 level. In this manner, the effects of table axis coupling and item table interaction can be determined without jeopardizing the safety of the test item. The digital drive signals are transferred initially to a 4-channel analog tape recorder via a set of digital to analog converters (DAC) housed in a CAMAC crate located in close proximity to the seismic simulator. During excitation of the test item analog to digital converters (ADC) are used to obtain digitized table response acceleration time histories from which the TRS's are generated. A comparison of the match between the TRS's and RRS's are made and appropriate adjustments to the drive signal α-weighting coefficients are made as in the preliminary shaping operation described above. The operation continues until the matching criteria associated with AMIN and BMAX are satisfied. A more complete description of the procedure can be found in Reference [13].

Eight different sets of earthquake signals were generated for the test program, each based on the R. G. 1.60 [9] response spectrum, Table 4-2, Section II.A. The first set, level 001, was the standard RRS with AMIN = 1.10 and BMAX = 1.40 which tended to force the test level to 1.25 times the RRS. The extended R.G. 1.60, level 002, consisted of a linear extension of the line from 3.5 to 9.0 Hz out to 20.0 Hz. This was done so that additional energy would be input in the electric rack at its resonances. AMIN and BMAX were again set at 1.10 and 1.40 respectively. The third, level 003, and fourth, level 004, sets of earthquake signals were identical to the first two except that AMIN and BMAX were set at 1.05 and 1.15 respectively. This was done to observe the effect of tolerance requirements on the results of the testing. The last two sets, levels 005 and 006, are identical to the first two except that no energy was input above 10 Hz and the low frequency levels were increased such that the TRS enveloped the RRS. The ZPA's for the six RRS described above was set at 1.0 g's. The final two test conditions, levels 011 and 012, took the RRS for level 001 and 002 and multiplied them by 2.0 over the entire frequency range giving a ZPA of 2.0 g's. Tests were performed using each of these eight signals for for both X-Z and Y-Z combinations of horizontal and vertical axes excitation.

Sine dwell and sine beat testing were also performed on the table mounted specimen. The sine dwell testing consisted of 30 second uniaxial and biaxial excitation at a number of frequencies. These included testing at resonances and nonresonance frequencies at input levels of 0.1 and 0.5 g's. The drive signal was derived using a function generator whose output signal was built up held and decayed by the operator such at the total time during the hold portion was a minimum of 30 seconds. The sine beat testing consisted of excitation at both resonance and nonresonance frequencies of 10 cycles per beat with a pause between beats. The pause time was adjusted to be either 0.5, 2.0 or 5.0 times the total beat period with a total test time of 30 seconds. Both these tests are representative of tests performed in the past for qualification testing.

The final set of table mounted testing consisted of simulation of a combined dynamic environment, earthquake and safety relief valve, SRV. The earthquake signals were such that the standard R.G. 1.60 RRS was enveloped. Both 2.0 and 5.0 second SRV signals were algebraically added to these signals during the stationary portion of the earthquake signal. The SRV signal was a band passed, 30-60 Hz, random signal which was multiplied by a half sine wave pulse of duration either 2.0 or 5.0 seconds. The level of the SRV was set such that the peak acceleration for the SRV alone was approximately 1.0 g. Three sets of runs; earthquake only, SRV only and earthquake plus SRV, were performed to check out various methods of analytically summing the corresponding signals.

For the table mounted testing two sets of data were recorded. The functional data, electrical state of the contacts on the devices, and the horizontal and vertical table accelerations were recorded on an oscillograph. This data was checked following each run to determine if chatter had occurred. An additional series of functional runs were performed on the Yarway Level Indicator to determine the effect of the water column on the functionality of the test items. A series of swept sine tests were performed for a number of hose lengths and initial differential pressure across the Yarway. No influence on the functionality of the device due to the water column was noted although a mechanical resonance of the level indicator was noted at 60 Hz. A total of eight accelerations and two displacements were recorded on magnetic tape for each test run. Two accelerations included the horizontal and vertical table accelerations. The horizontal and vertical table displacements were also recorded. Therefore for each test run a total of six elevated response accelerations were obtained. In most cases two runs were performed for each earthquake signal so that a total of nine elevated conditions were recorded. Three elevated locations were recorded twice to obtain an indication of repeatability. This data was recorded on magnetic tape for later digitizing and analysis using the DEC PDP 11/70.

The digitizing processes is carried out using a system developed at SwRI and controlled by the DEC PDP 11/70 computer. The equipment consists of 14 channels of 1/6 octave bandpass filters and operational amplifiers, and 14 channels of high speed A/D converter housed in a CAMAC crate. For this series of tests the analog signal was passed through a high pass filter (1.3 Hz) and a low pass filter (315 Hz) and digitized at a rate of 512 samples per second. After the data has been digitized and converted to engineering units, analysis of the data can be performed. Programs are available to calculate and plot the following information: time histories, time internal RMS values, shock response spectra, PSD over any time interval, coherence over any time interval, probability density function over any time interval, addition of two PSD files, SRSS of two shock response spectra and the shock response spectra to power spectral density function transformation. Each one of these programs is resident or the DEC PDP 11/70 and available for use as required.

5.0 ANALYTICAL MODEL OF ELECTRICAL RACK

Qualification of equipment for use in nuclear power plants can be done either through testing, analytically, or by combined testing/analytical procedures. For testing the equipment is mounted on a seismic simulator and subjected to the postulated seismic event. The functionality of the test equipment is monitored prior to, during and after the event to insure proper operation. In addition, the structural integrity of the equipment is checked between test runs. Analytical qualification is usually performed on equipment which is too large to test and where performance is primarily a function of structural integrity.

An analytical model of the equipment to be qualified is developed, in most cases using finite element (FEM) methods, from which the dynamic characteristics of the equipment can be estimated. Using these dynamic characteristics; modal frequencies, shapes and masses, the structural response of the model can be predicted for a postulated seismic event using either a time history or modal superposition approach. The accuracy of most analytical models is dependent upon a number of factors including; degrees of freedom present, FEM elements used to model the structural system (i.e., rods, beam, solids, plates, etc.), mass distribution, dimensional accuracy and boundary condition. The analysis can either be linear or nonlinear depending upon the nature of the structure being modeled.

It is extremely difficult to determine analytically the functionality of equipment or instrumentation mounted on a large structural system. This is where the combined testing/analytical approach comes into play. The overall structural system can be modeled with dummy masses in place of the equipment and instruments. By subjecting the model to the postulated event the responses at elevated positions can be obtained. These elevated responses are in turn used as test parameters for dynamic testing of the equipment or instrumentation. The functionality of electrical, mechanical and hydraulic equipment can be checked in this manner. This report deals with phases of each of the three approaches to qualification. In this section the development and verification of an analytical model of the electrical panel will be discussed.

5.1 Model Synthesis

The structural model of the electrical rack was an FEM model using the STARDYNE Structural Analysis System. Information required to develop the model; dimensions, structural members, material properties, masses and connection were obtained from drawings of the electrical rack used in its construction and standard engineering sources. Verification of the dimensions, masses and structural elements was obtained from measurements taken of the electrical rack but these were not used in the model development. The FEM model, Figure 5.1-1, had the following characteristics:

Number of Nodes - 265
Number of Nodes with Restraints - 26

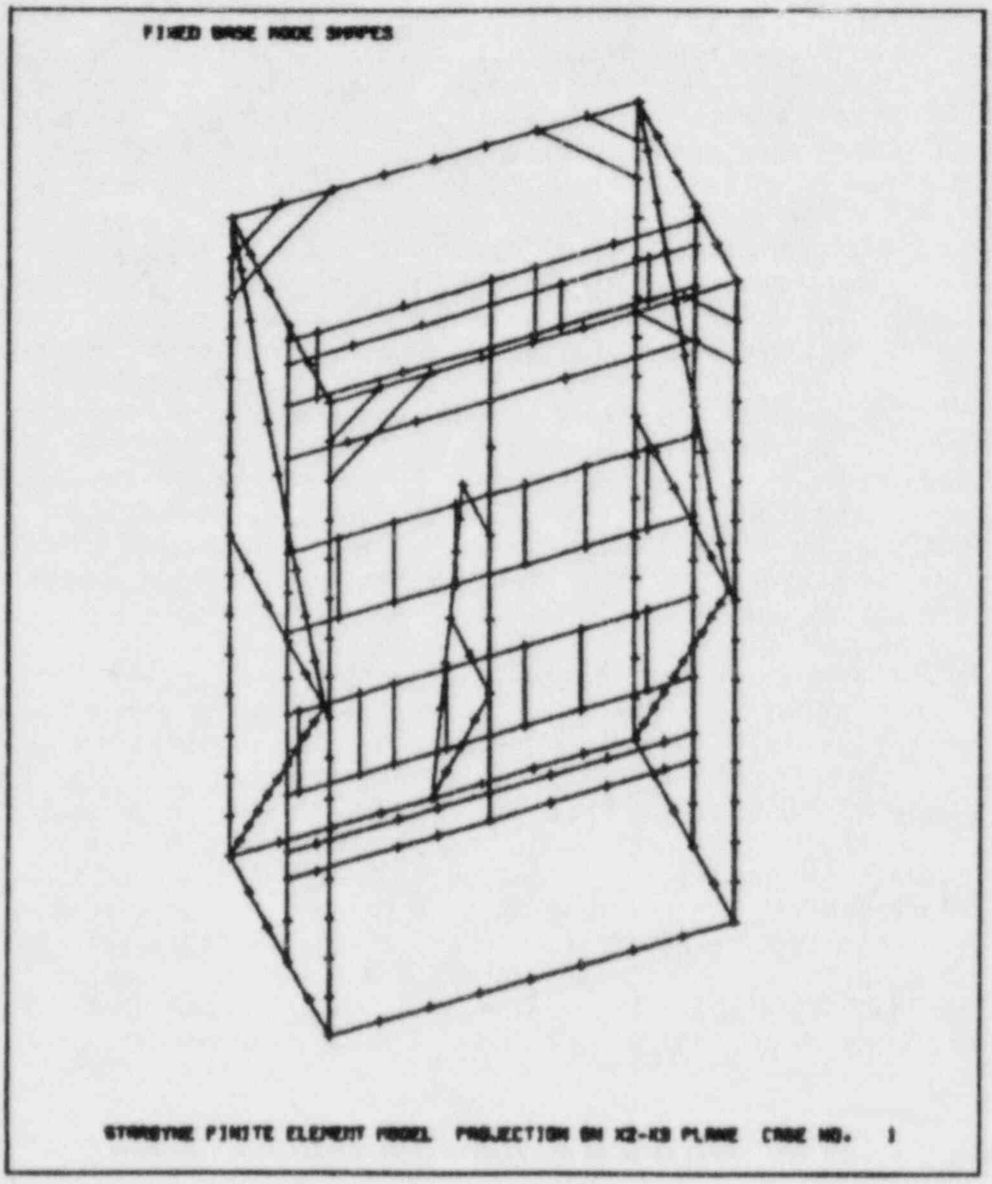


Figure 5.1-1. Finite Element Model of Specimen

Degress of Freedom - 1456
Mass Degrees of Freedom - 717
Added Weight at 53 Nodes - 240 lbs
Total Weight - 722 lbs
Number of Elements:
    Elastic Beams - 305
    Massless Beams - 17
    Quad-Plates - 4

The number and spacing of the nodes was based initially on obtaining accurate modal information out to 100 Hz. For a simply supported beam of uniform section and mass the first natural frequency, ω_1, is given by

$$\omega_1 = \pi^2 \sqrt{\frac{EI}{\mu \ell^4}} \text{ rad/sec} \qquad (5\text{-}1)$$

where E = Youngs modulus, lb/in^2
I = Area moment of inertia, in^4
ℓ = length of beam, in
μ = mass per unit length, lb-sec^2/in^2

This will give a lower bound on the frequency of the structural elements where the fixed-fixed beam formulation will tend to give an upper bound. Using this and the physical characteristics of the structural members the maximum distance between support was found to be 22.9 inches for the channels. In order to resolve the 100 Hz frequency the maximum distance between nodes should be no more than half this. Since there were concentrated masses along the length of the beams and to better resolve the system an average distance between nodes was set at 6.0 inches. This actual distance varied throughout the structure to account for variation in the length of elements between connections and the location of instrumentation and masses. The nodes of all major structural elements, the 2-1/2 x 2-1/2 x 1/4 angles, were defined to lie along a line at the angles' center of gravity, cg. The majority of all nodes were placed near the center of gravity of the structural element in question. The major exception was the central vertical support on the instrument rack. The nodes for this element were at the cg of the horizontal elements which were foward of the vertical angle. To account for this the beam was defined to be offset from the nodes by the required amount.

All nodes were initially defined to have six degrees of freedom. To account for the welding to the baseplate all nodes on the lower rectangle were restrained against translation in all three directions and rotation about the two axes perpendicular to the length of the beams. Rotation about the length of the beam was allowed to reflect actual conditions, the angles were welded along only one side thereby allowing some rotation. There were a total 1456 DOF on the structure. Since STARDYNE does not calculate for rotational inertia at each node point, there were only 717 translational DOF to be used in the solution of the eigenvalue problem.

The structural elements were assumed to be uniform in mass and cross ection. The STARDYNE programs uses a diagonal mass matrix with all masses concentrated at the node points. In addition to the structural mass the model took into account the masses of the instruments, their supporting plates, and the masses defined previously, Section 4.1. The mass of the instrument and their support plate were evenly distributed over the support points. Either two or four support points were defined for each instrument depending on the width of the support plate. The masses were placed at the local node points and no compensation made for the fact that most instrumentation cgs were forward of these points. This simplification limited the amount of coupling in the model. The total weight of the model as calculated by STARDYNE was 722 lbs. This did not include the baseplate weight of 734 lbs, bringing the total weight of the test specimen to 1456 lbs.

Three different structural elements were used to model the electrical rack. The channels, angles, and UNISTRUT members were modeled using an elastic beam with six degrees of freedom at each node. The properties of each beam: cross-sectional area, torsional constant, moment of inertias and shear shape factors were obtained from available literature. The massless beams were an attempt to model the stiffness of the support plate/instrument combination. In the vertical directions these added stiffness and prevented the two UNISTRUT members from separating. On the other hand these added little resistance against rotation of the instrument groups and torsion of the UNISTRUTs. The massless beams were used because they would not enter into the eigenvalue solution mass matrix, although their stiffness would produce the required effect. Four plate elements were used to represent the gussets in the upper corners of the frame.

The material properties are those commonly accepted for steel structural members. These include:

Youngs Modulus	- 28.0×10^6 psi
Shear Modulus	- 10.8×10^6 psi
Poissons Ratio	- 0.3
Density	- 0.283 lb/in^3

An eigenvalue solution, based on the Lanczos modal extraction procedure, was the only analysis performed on the model using STARDYNE. The mode shapes, frequencies and masses were obtained for a number of modes. Additional analysis was performed on the DEC PDP 11/70 using inhouse programs and the results obtained from the STARDYNE eigenvalue solution.

5.2 Model Verification

Verification of the model consisted of two phases, checks of the model itself, and comparison of the eigenvalue solution results to measured frequencies and mode shapes. The first consisted of checking the location of the node points, structural element properties and connectivity and mass distribution. This was done by careful analysis of the STARDYNE printed output and plots of the geometry. The second consisted of extensive comparisons of results obtained during the structural identification testing to the model eigenvalue solution.

A summary of the modal studies is given in Table 5-1. Analytical frequencies and mode shape plots were obtained from STARDYNE runs. The preliminary floor mounted results include the swept sine, random, and impact hammer testing done at the beginning of the program. From the swept sine and random testing the natural frequencies were easily obtained although visualization of the mode shapes was difficult. The peaks of the transfer functions were subsequently checked against the impact and analytical mode shapes to determine the corresponding mode shapes. Two orientations of the frame were used during the testing corresponding to X-axis excitation, N-S orientation, and Y-axis excitation, E-W orientation. The frame is rotated ninety degrees and remounted to the floor for each configuration. For the first three modes the results for the N-S orientation are always lower than the corresponding results for the E-W orientation. The first three modes are the first two bending modes and torsion of the frame, which will be affected by mounting conditions. The higher modes are primarily modes of the instrument rack and would not be affected as much. The preliminary impact testing provided a better insight into the respective mode shapes. Due to the complexity of the mode shapes above mode Number 4 it is extremely difficult to accurately compare results. Therefore, most of the comparisons in Table 5-1 above the fourth mode were based on engineering judgement. The damping values obtained from the preliminary testing were obtained using the log decay procedure. The low value of damping of the structure makes accurate measurement difficult. The detailed impact floor mounted testing provided additional information on the mode shapes, frequencies, damping and masses. Samples of the mode shapes are given in Figures 5.2-1 to 5.2-4. This series of tests consisted of measurements of the response in the two horizontal directions at a total of fifty node points. These node points were chosen because they represented major structural elements and instrument locations. Some analytical modes were not resolved during the testing because no measurements were made at locations whose motion was dominate for these modes. In setting up these experiments one must be extremely careful in defining the nodes to obtain enough information so that qualification can be performed and that test times are not excessive. The damping and modal masses were obtained during this last testing sequence using a circle-curve fit procedure in the ZONIC system.

A final series of impact tests were performed to determine variability that can be expected as a result of mounting. For this series of tests the electrical rack was excited at a single point and the response measured at several points. Table 5-2 is a summary of the results obtained. As noted earlier, the orientation has an effect on the resulting natural frequencies. For a given orientation the values are consistent even though, as with the first two sets of data, the testing was performed more than one month apart. The variations due to the amount of torque on the bolts are not significant, refer to E-W orientation pretorque and torqued tests. It seems in both cases there was sufficient contact to provide consistent results. The final test was a repeat of the earlier test after the frame had been lifted and retorqued to the floor. Again no significant change was noted for these test conditions.

The first three modes are the first side-to-side, fore-aft and torsional modes of the frame respectively, Figures 5.2-1 to 5.2-3. On

TABLE 5-1
MODAL SURVEY OF ELECTRICAL RACK

Anal. Model		Preliminary Floor Mounted Data Sine Data			Random Data		Input Data E-W Orientation		Detailed Impact Floor Mounted N-S Orientation		
Mode No.	Freq. Hz	N-S Orien. Freq.	E-W Orien. Freq.	Damping*	N-S Orien. Freq.	E-W Orien. Freq.	Ins.Rack Model Freq.	Frame Model Freq.	Freq.	Damping**	Description
1	14.6	12.8	13.5	0.5%	-	13.3	13.5	13.3	11.6	1.7%	Side-Side Bending of Frame and Instrument Rack
2	24.4	25.9	-	3%	24.7	-	27.8	27.2	23.4	1.2%	Fore-Aft Bending of Frame and Instrument Rack
3	40.5	33.5	36.2	3%	33.1	35.1	36.0	35.9	30.9	0.8%	Torsion of Frame
4	42.8	38.1	-	2%	37.1	38.4	40.0	39.5	44.7	1.9%	Fore-Aft Bending of Instrument Rack Top and Bottom Out of Phase
5	50.4	46.7	-	-	46.1	46.2	45.5	46.7	50.0	0.5%	Fore-Aft Bending of Instrument Rack, Flapping of Back Support
6	52.4	-	-	-	50.9	50.3	50.8	51.0	***	-	Fore-Aft Bending of Bottom Channels
7	53.9	-	-	-	-	-	52.5	52.5	***	-	Flapping of Back Support
8	55.2	56.8	-	0.8%	55.4	-	56.8	56.8	54.1	1.3%	Twist and Bending of Side Frames, Minor Fore-Aft Bending of Instrument Rack
9	57.4	64.9	63.5	0.4%	62.8	63.0	63.6	63.5	59.4	0.8%	Twist and Bending of Side Frames, Fore-Aft Bending of Instrument Rack
10	62.3	-	-	-	-	-	60.0	60.2	61.8	1.2%	Fore-Aft Bending of Frame, Second Mode Fore-Aft Bending of Top Instrument Group
11	73.1	-	-	-	-	-	67.0	-	***	-	Second Mode Fore-Aft Bending of Bottom Channels
12	76.0	-	72.0	0.2%	-	71.6	72.0	72.1	***	-	Twist of Top Instrument Rack, Second Mode of Top Channel
13	84.9	75.5	74.0	0.5%	73.7	73.9	73.9&75.7	73.8	80.3	1.5%	Twist and Bending of Side Frames, Second Mode of Top Instrument Group
14	85.6	-	81.9	0.3%	81.2	80.8	80.5	80.9	****		Side-Side Bending of Frame and Instrument Rack
15	89.6	83.3	-	0.2%	-	-	83.2	-			Fore-Aft Bending of Upper Channel
16	91.5	-	-	-	-	-	86.3	84.8			Breathing of Frame
17	99.8	-	-	-	-	-	96.7	-			Fore-Aft Bending of Top Two Instrument Groups
18	100.8	-	-	-	-	-	86.3	-			Instrument Rack Bending
19	106.2	-	-	-	-	-	-	-			Side-Side Bending of Frame, Fore-Aft Bending of Instrument Rack
20	110.6	-	-	-	-	-	93.0	-			Fore-Aft Bending of Lower Channels

* Log Decay ** Zonic Circle Curve Fit *** Not determined because no response was measured on these channels

**** Higher Modes not analyzed.

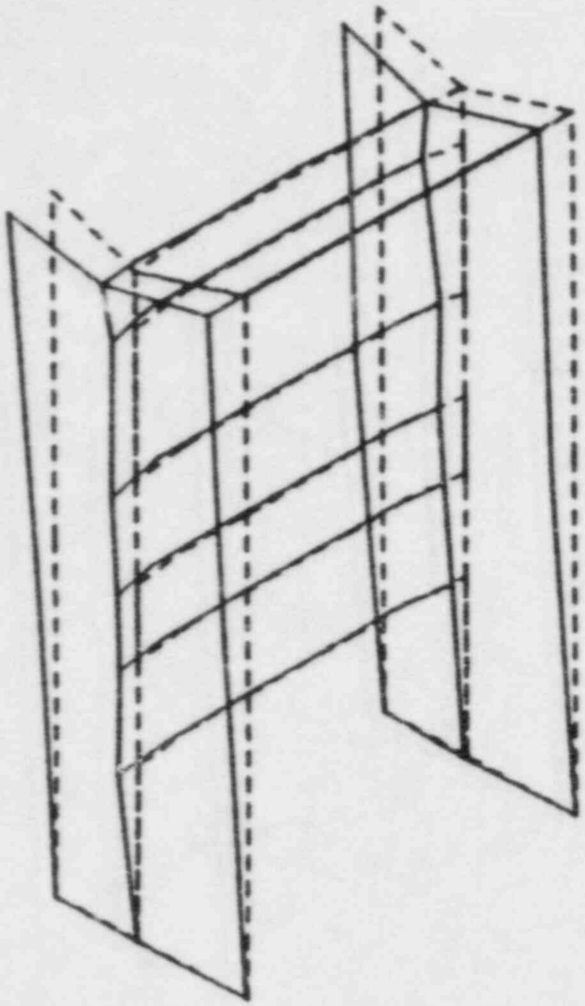


Figure 5.2-1. Mode 1, 11.6 Hz Side/Side Bending of Frame

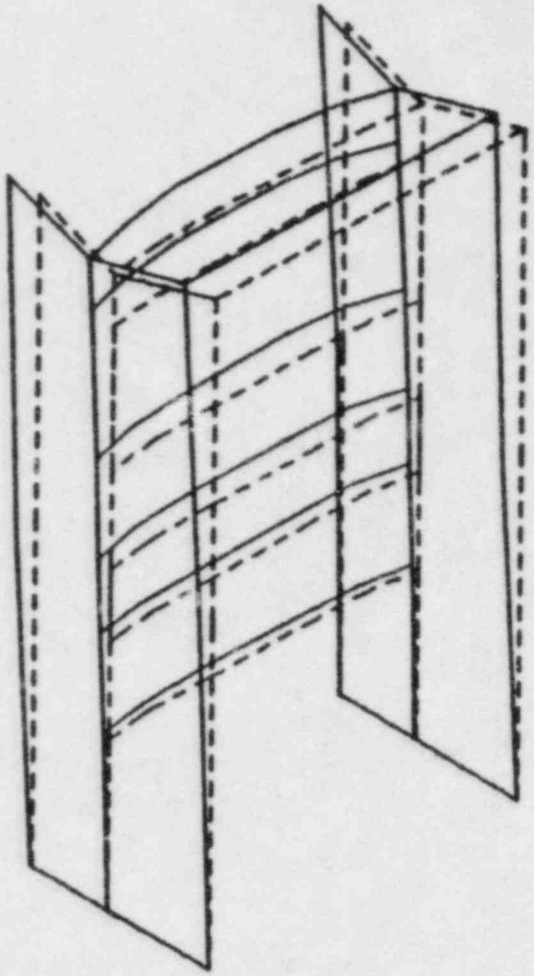


Figure 5.2-2. Mode 2, 23.4 Hz Fore/Aft Bending of Rack Top and Frame

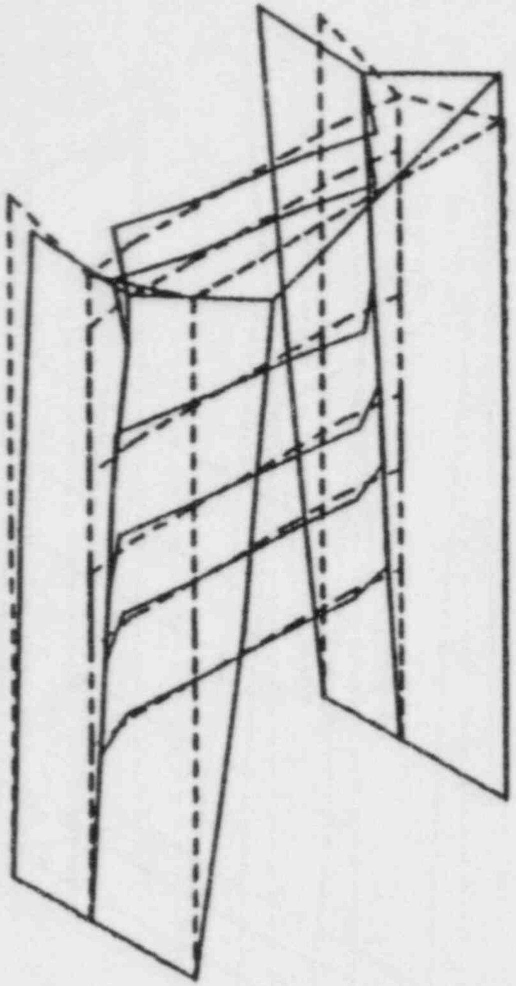


Figure 5.2-3. Mode 3, 30.9 Hz Torsion of Frame

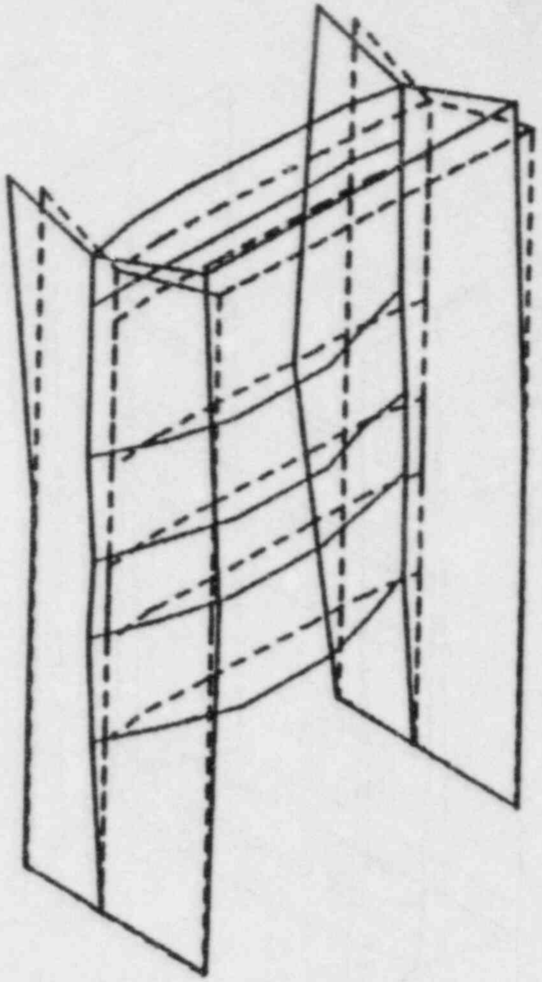


Figure 5.2-4. Mode 4, 44.7 Hz Second Fore/Aft Bending of Instrument Rack

TABLE 5-2. VARIATION IN FREQUENCIES DUE TO MOUNTING CONDITIONS

Condition	Orientation	Frequency (Hz) Mode No. 1	2	3
Detailed Impact Floor Mounted	N-S	11.6	23.4	30.9
Retest of Above	N-S	11.6	23.4	30.9
Pretorque Impact Test	E-W	12.1	24.4	33.8
Torqued Impact Test	E-W	12.1	24.3	33.6
Torqued Repeat of Above	E-W	----	24.4	33.8
Mean		11.9	24.0	32.6

the figures the initial shape is given by the dashed lines and the displaced shape by the solid lines. Similar plots were obtained for the initial impact testing and the STARDYNE model but are not included. After the first three modes the response is dominated by vibration of the instrument rack and its components. The complexity of the higher modes made exact comparisons difficult.

6.0 STUDIES OF SPECIFIC TECHNICAL ISSUES/ANOMALIES FOR ELECTRICAL RACK

A discussion of the previously identified technical issues/anomalies associated with the qualification of equipment for nuclear power plants is given in Section 1.2 and Reference [1]. The objective of this test program is to provide some information on the influence of these issues on the qualification procedure. Information on those that are considered to be significant has been obtained, although resolution of their influence on the qualification procedure has not been completely answered. This is to be performed in subsequent tasks of this program.

6.1 Structural Mode Identification and Verification

A number of procedures are commonly used to determine the frequency response of a structure. These include: 1) swept sine, 2) pseudo-random, 3) periodic chirps, 4) pure random, 5) periodic random, 6) impact testing, 7) unit step function testing, 8) chirps and 9) operating inputs [14]. Each of these test procedures has specific advantages and disadvantages. Of those listed only swept sine, pure random, and impact testing were performed during the testing described in this program. The specific advantages and disadvantages of these types are: [14]

Swept Sine Testing

Advantages

1) It has the best (lowest) peak to rms energy ratio.
2) It has the best signal to noise characteristics.
3) It is good for documentation of the non-linear characteristics of the test system.
4) It has the longest history of use and as a result, it is the most widely accepted input.

Disadvantages

1) For non-linear systems the results are a poor linear approximation of the non-linear system. Therefore the linear curve fitting models used to obtain the modal coefficients do not give good results.
2) It is slow.

Pure Random

Advantages

1) It gives the best linear approximation of a nonlinear system.
2) It is relatively fast.
3) It is well controlled. The force levels can be easily and accurately controlled.
4) It has good peak to rms values.

Disadvantages

1) For lightly damped systems, the frequency resolution of the discrete Fourier transform can be a seriously problem.
2) It is difficult to control the frequency spectrum.

Impact Testing

Advantages

1) Setup and fixturing time are a minimum of all the excitation techniques.

2) Equipment requirements are the least of all the testing methods.
3) It is the fastest test method for low noise environments.
4) It is ideal for use in tight quarters where an exciter will not fit.

Disadvantages

1) It has a very high peak to rms energy ratio and is therefore not suitable for highly nonlinear systems.
2) It has poor signal to noise characteristics.
3) Special care must be taken to eliminate overload to system, signal processing equipment and/or the data analysis equipment.

6.1.1 Comparison of Test Methodologies

Sample results for the preliminary floor mounted testing for the three methods are given in Figures 6.1-1 to 6.1-3. For the swept sine testing, Figure 6.1-1, the sweep rate was set at 0.5 octaves/minute with an input level of 25.0 or 2.5 lbs force depending on the axis of excitation. The sweep rate was decreased near resonances in an attempt to accurately resolve the frequency and amplitude. Note that all sweeps were made from 1.0 to 100 Hz so there could be some shift in indicated frequency upward as well as a decrease in the amplitude at resonance compared to the steady state value. It is appropriate to predict how sensitive the resulting errors are to sweep rate. The variation of frequency and amplitudes for a linear sweep rate has been studied by a number of individuals [15, 16]. For the case of a logarithmic sweep rate as used herein, a closed form solution does not appear possible. Morse [17] has proposed a solution although we felt that his initial assumptions are incorrect. Therefore, in order to obtain more information, responses were measured with an analog circuit and compared to the analog results presented in Reference [17]. The analog circuit modeled a base excited single degree of freedom damped oscillator with adjustable frequency and damping. For a 40 Hz oscillator the shifts in frequency noted were not as sensitive to the damping as reported by Morse. The shifts were primarily a function of sweep rate and only weakly dependent on damping. Current tests showed lower ratios of amplitude than noted in Reference [17]. For a 0.5 octave/minute sweep rate the ratio of the current results to Morse's results are from 1.0 to 0.94. This ratio varies from 0.94 to 0.35 for a sweep rate of five octaves per minute as damping is decreased from 10% to 1%. Cronin [18] developed an approximate analytical expression to determine the amplification as a result of a swept sine testing. As with Morse's results, these analytical expressions predict more response than was measured during the current testing.

The random testing, Figure 6.1-2, consisted of broad band excitation at a level of approximately 25 or 2.5 lb rms force. A total of fifty averages with a 0.31 Hz bandwidth of resolution were taken for each measurement point. As with the swept sine data the results of the random testing will have errors in both the frequency and amplitude. The frequency should vary no more than plus or minus the bandwidth of analysis. Errors associated with the amplitude of the transfer function are a function of both the number of sample averages and the coherence

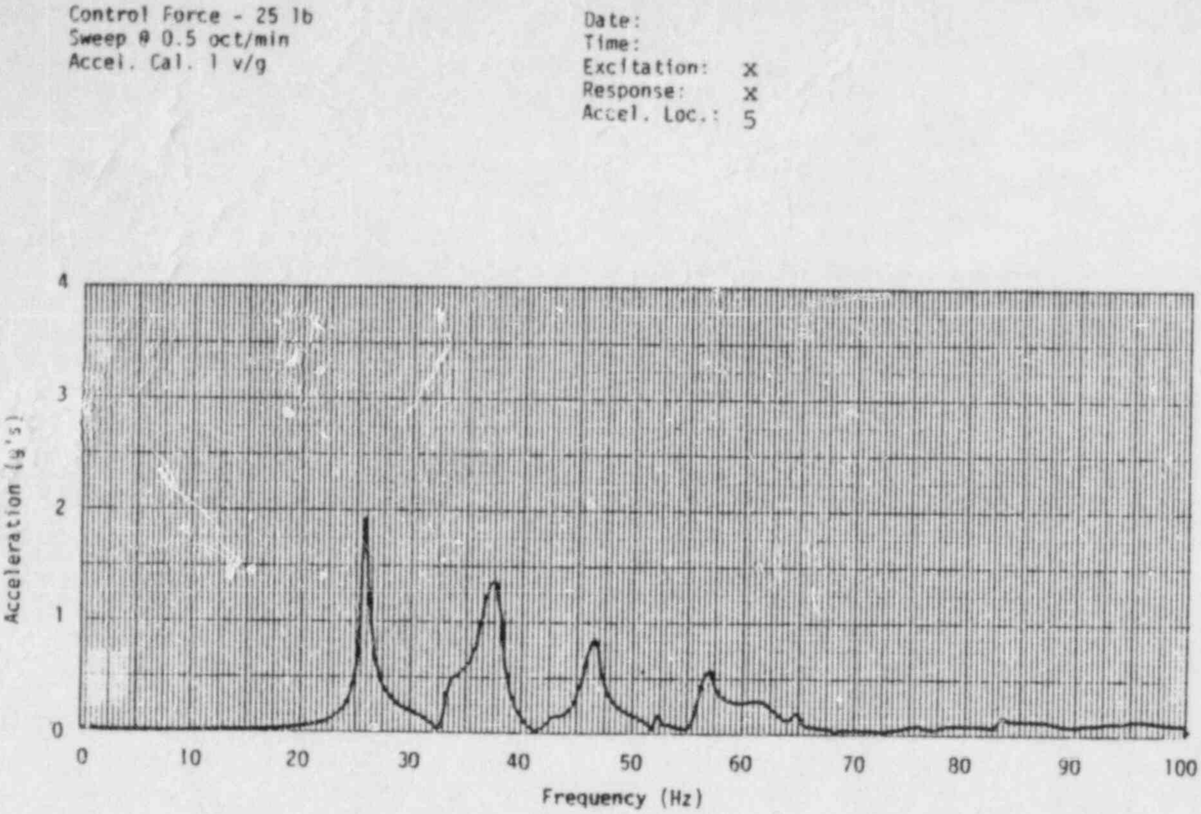


Figure 6.1-1. Sine Sweep Transfer Function at Position 5 With Floor Mount

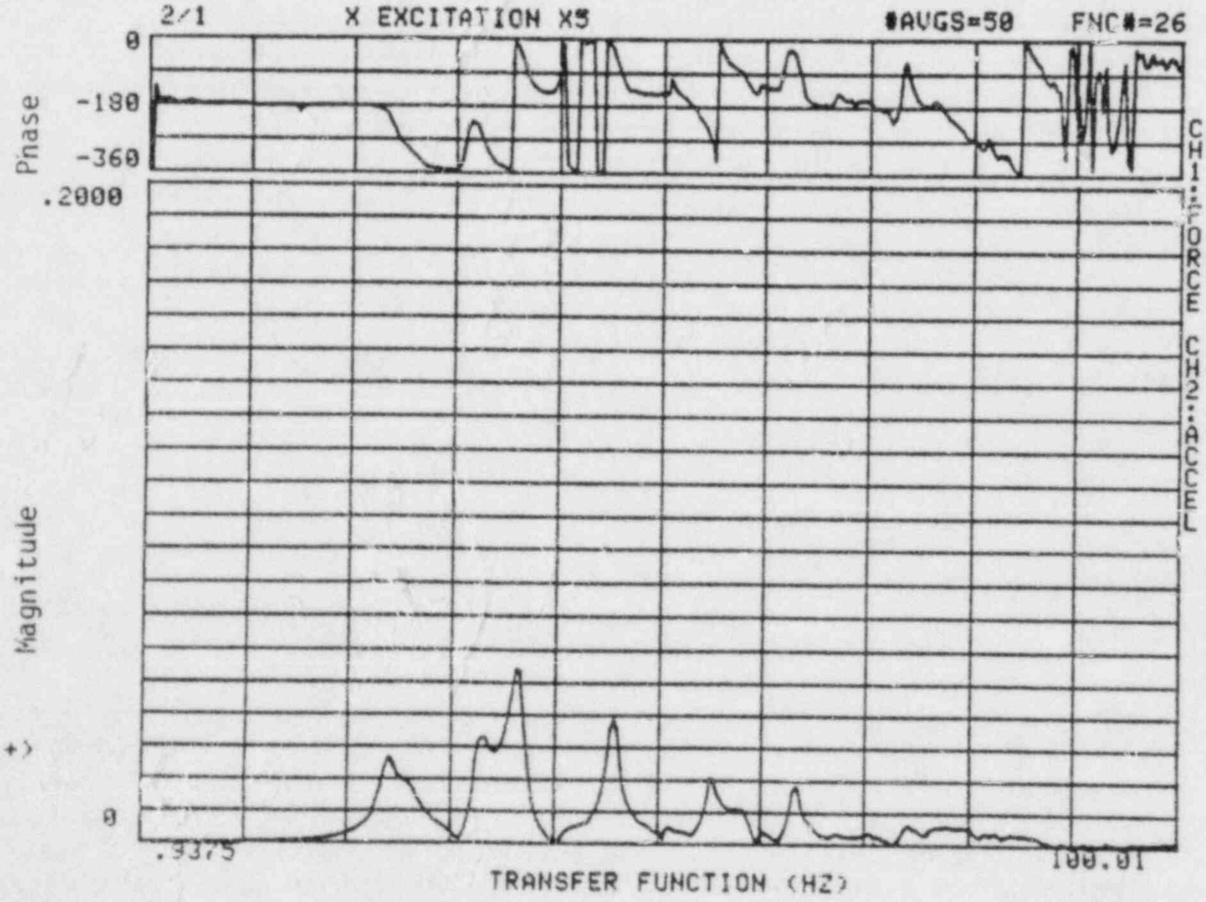


Figure 6.1-2. Random Excitation Transfer Function at Position 5 With Floor Mount

between input and ouput [11]. No coherence values were obtained during the random testing, therefore a value of 0.80 will be assumed. (This should give a conservative estimate.) The normalized random error for fifty samples was determined to be 0.075 [11]. This indicates that the number of samples was sufficient to determine an accurate value although the bandwidth of analysis may have been too large for the true level to be indicated.

The resonance frequencies obtained using the swept sine and random methods are similar although in all cases the random frequencies are slightly lower, 26 vs. 25, 37.5 vs. 37, 46.5 vs. 46 and 57 vs. 55 Hz. This shift is to be expected as discussed above. A second discrepancy is the relative amplitude of the first three peaks. The swept sine data has a higher level at 26 Hz than the corresponding random level. Since this mode is lightly damped the source of error is probably the frequency of resolution of the random data, 0.31 Hz. For this low frequency and damping the true amplitude cannot be obtained using random testing unless the ZOOM option is used, which can give a better definition of this local region. The relative amplitudes of the second two frequencies are similar because the damping is higher for these modes. The half power points for these higher modes are further apart so the amplitude will be resolved to a higher degree.

The impact hammer results, Figure 6.1-3, show some of the problems associated with this type of testing. For this test a total of five averages were taken at each measurement point with a 0.31 Hz bandwidth of resolution. The hammer used to perform this testing was extremely light and excitation of the low frequencies difficult. Because of the variation in the levels of input between these three methods, swept sine, random and impact, the impact results show a much less damped response. The structure is not excited as much and therefore does not work as much resulting in a lower indicated damping. The relative amplitude between the first and third modes are shifted when compared to the sine testing. This is once again due in part to the frequency resolution of the analysis. The second mode, at 37.5 Hz, is not evident at all in the impact testing results. This could be due in part to a shift in the location of this measurement point for the impact testing from the back of the instrument to one of the UNISTRUT supports. This was done to allow for excitation using the hammer. By looking at the mode shape results this point is closer to a node point and would show less response. The majority of the problems associated with the impact testing were later resolved by using a large hammer and the ZOOM option. The results described above are similar to those noted at the other locations where measurements were made.

The electrical rack was then placed on the seismic simulator and an additional series of structural identification testing performed. Sine swept testing consisted of excitation at 0.1 g's peak at the base over the frequency range 3 to 100 Hz (Figure 6.1-4). Below 3 Hz it was difficult to control the level of excitation. The procedures for the random testing were similar to the floor mounted test, except the level of the base excitation was 0.12 g's rms. The number of averages and bandwidth of resolution were identical (Figure 6.1-5). There is a significant difference between the results for the swept sine and the

Floor Mounted

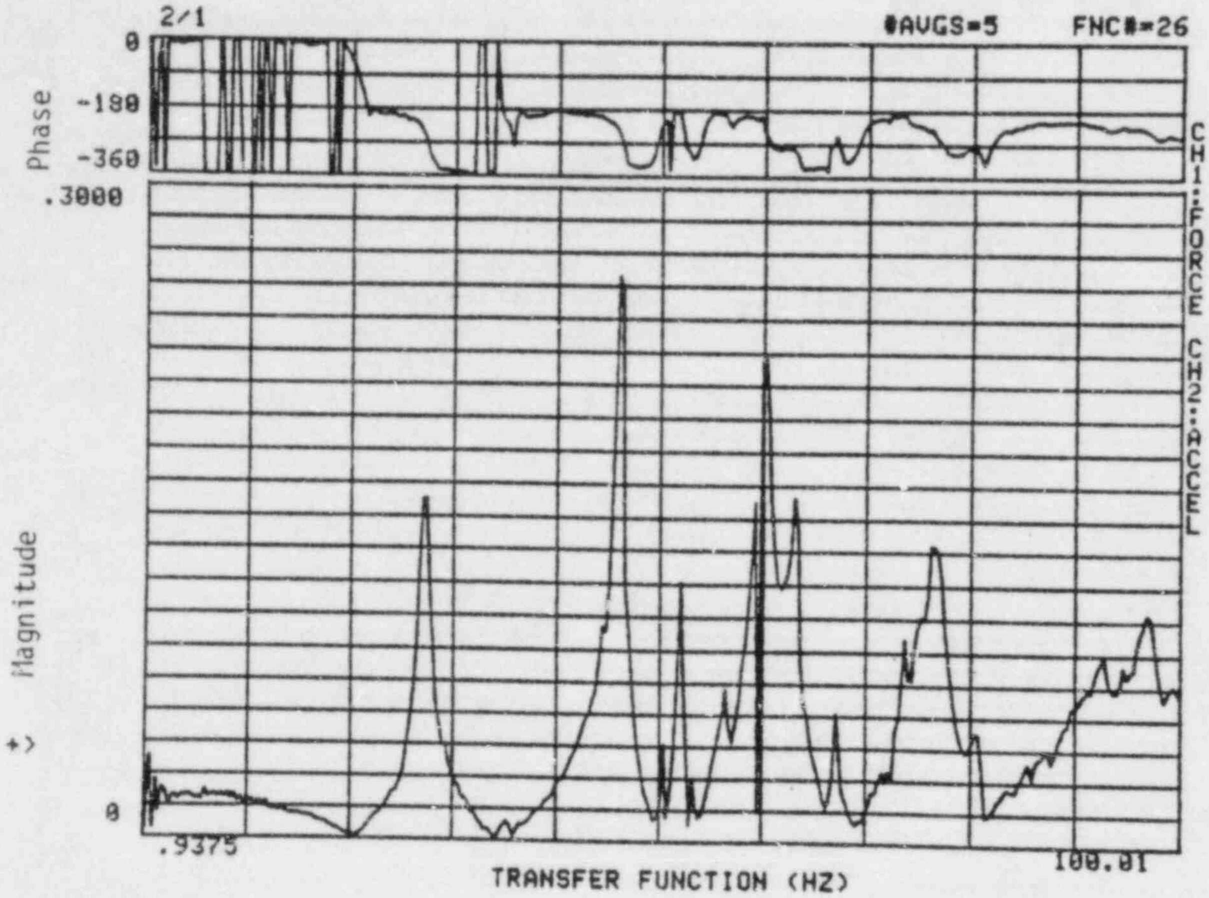


Figure 6.1-3. Hammer Transient Transfer Function at Position 5 With Floor Mount

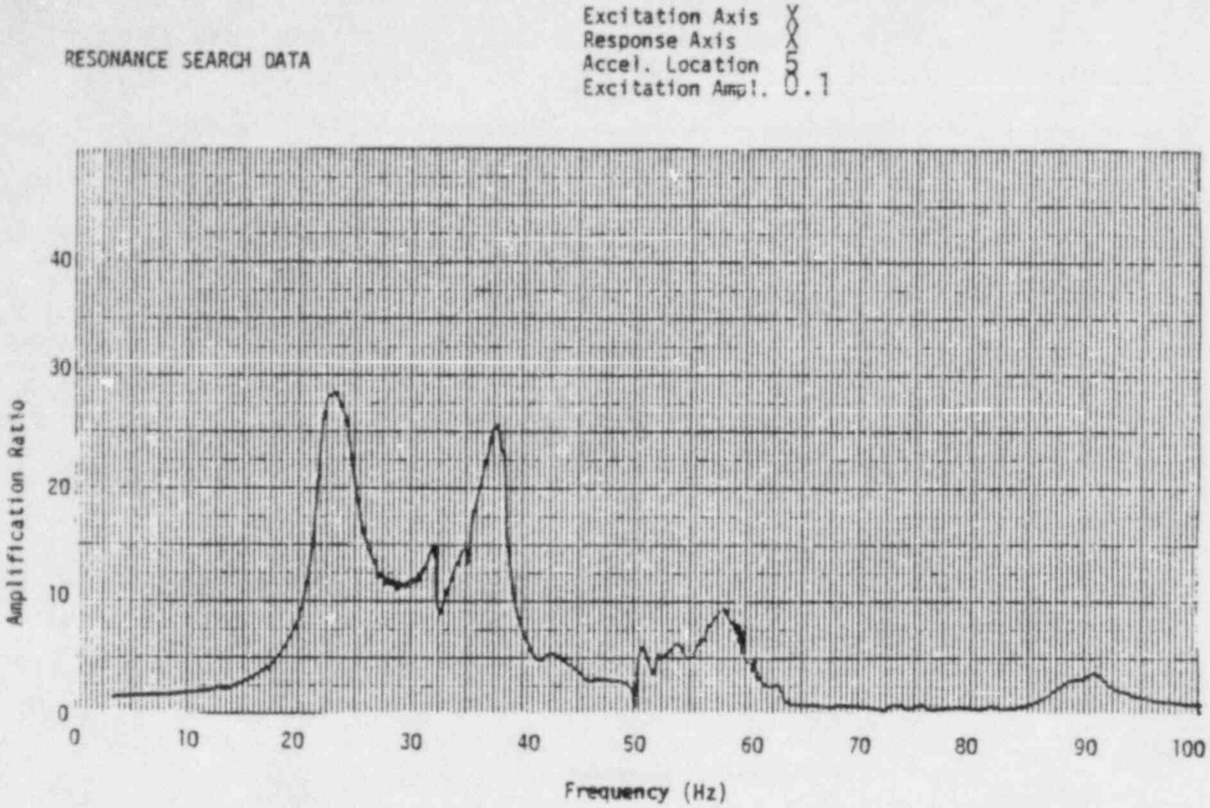


Figure 6.1-4. Position 5 Transfer Function for Sine Sweep With Fixed Vertical Table

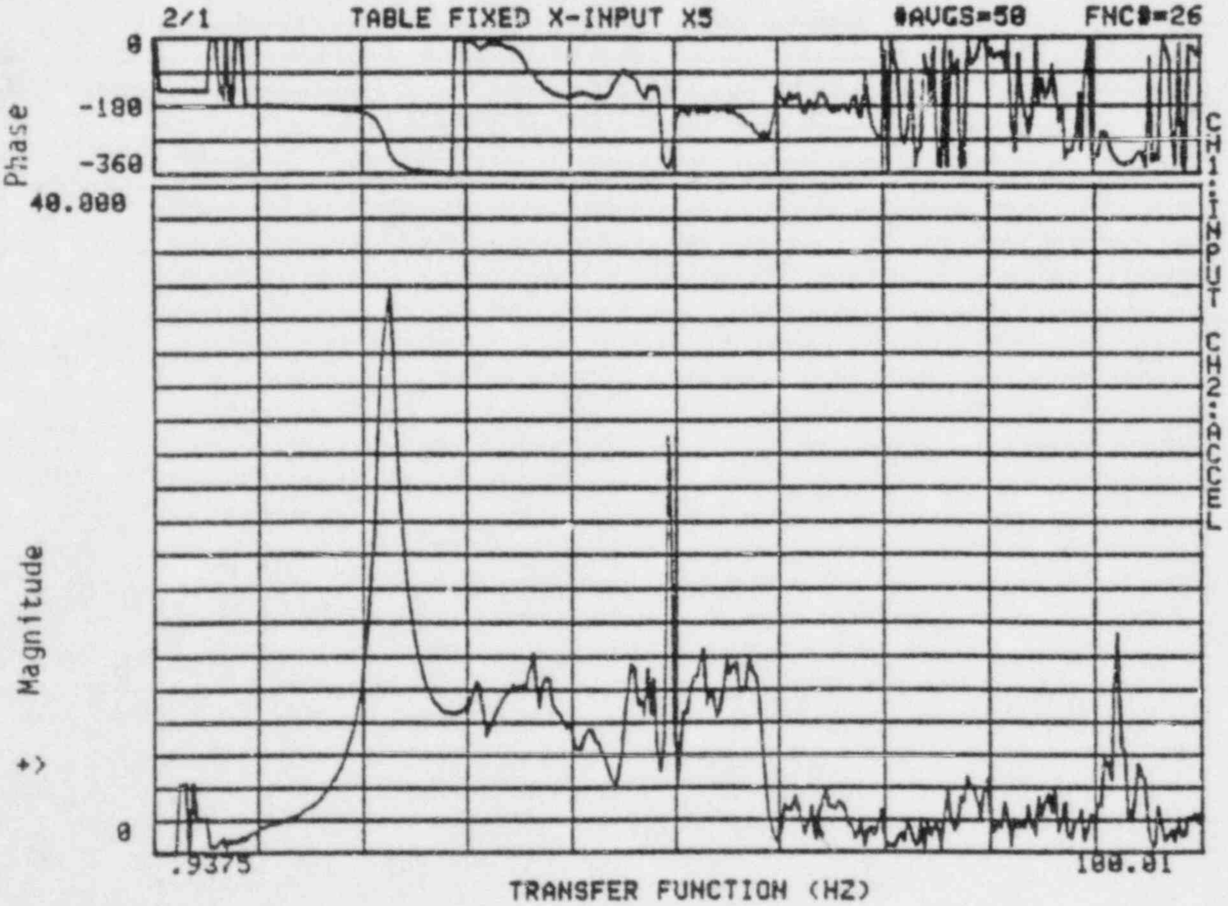


Figure 6.1-5. Position 5 Transfer Function for Random Excitation With Fixed Vertical Table

random testing. The first mode responses, at 23 Hz, are similar for both procedures. By looking at both the phase and amplitude results near 37 Hz for the random testing a mode can be picked out although its amplitude is significantly less than the sine results show. The reason for this discrepancy is not yet completely resolved. Above 70 Hz the data for the random testing is highly questionable. The rapid oscillation in the phase results indicate that the level of excitation was extremely low and measurement noise will tend to dominate the results. Calculation of coherence would indicate the source of the problems although at the time of testing none was made.

One important thing that must be considered for each of these test procedures is the energy content of the excitation. Because of the nature of the swept sine testing the amount of excitation at each frequency can be accurately controlled. This is one of the main advantages of the procedure. For the pure random testing the energy levels at all frequencies must be kept as equal as possible, i.e., white noise. For the floor mounted random testing this was done (see Figure 6.1-6). Therefore one would expect the results to be similar to the sine swept results, considering all other aspects equal. This was partially true as described above. An example of the PSD for the random table mounted testing is given in Figure 6.1-7. As can be seen, the level rolls off with increasing frequency. In addition there are a number of dips which occur at the resonances of the system, electrical panel and table. In theory the signal processing is able to take care of this unequalized input level although a problem occurs because the resulting signal to noise ratio is small which makes analysis difficult. This is evident by the results shown in Figure 6.1-5.

An amplitude spectrum of the impact hammer excitation for the detailed structural identification testing is given in Figure 6.1-8. The level is fairly flat within the frequency of range of interest. Similar results for the preliminary structural identification testing showed a greater variation in level for the same frequency range with an overall reduction in total energy, both of which make analysis more difficult. The improvement in the results of the impact testing can be seen in Figures 6.1-9 and 6.1-10. These are the results for the second series of tests. Figure 6.1-9 is the amplitude and phase averaged transfer function using a log scale on the amplitude portion. Figure 6.1-10 is the real and imaginary parts of the averaged transfer function.

As with all types of testing there will be an error associated with the results obtained for impact testing. During the impact studies to determine the influence of mounting conditions on the natural frequencies of the electrical rack the coherence was obtained, Figure 6.1-11. This indicates that above 5 Hz the measured response of the structure is a direct result in the input. From [11] for a random error in the coherence of 0.1 the true coherence will be 0.92 for the five data samples taken. Using this the normalized random error in the amplitude of the transfer function was calculated to be 0.13. A large number of samples would be required to reduce this value.

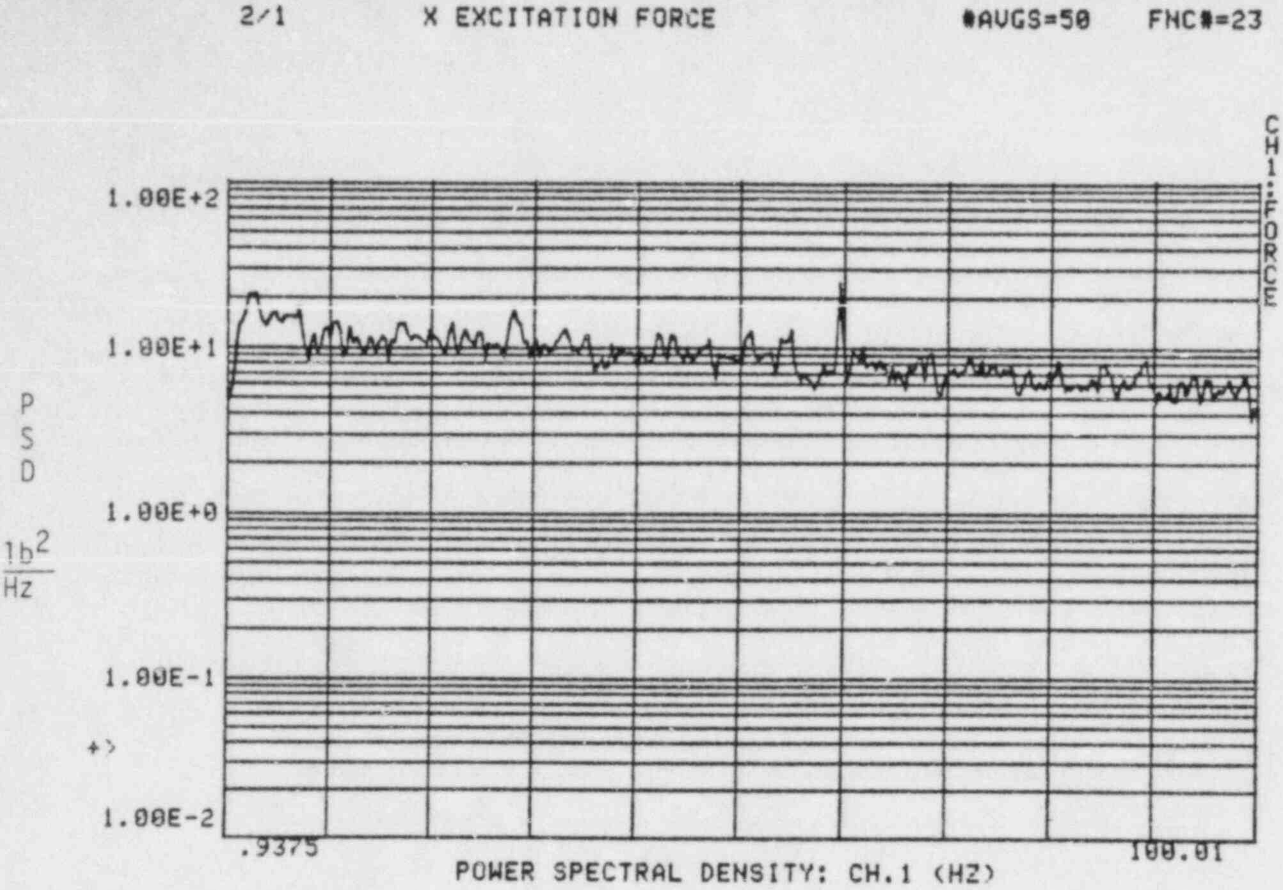


Figure 6.1-6. Power Spectral Density of Single Point Random Excitation With Floor Mount

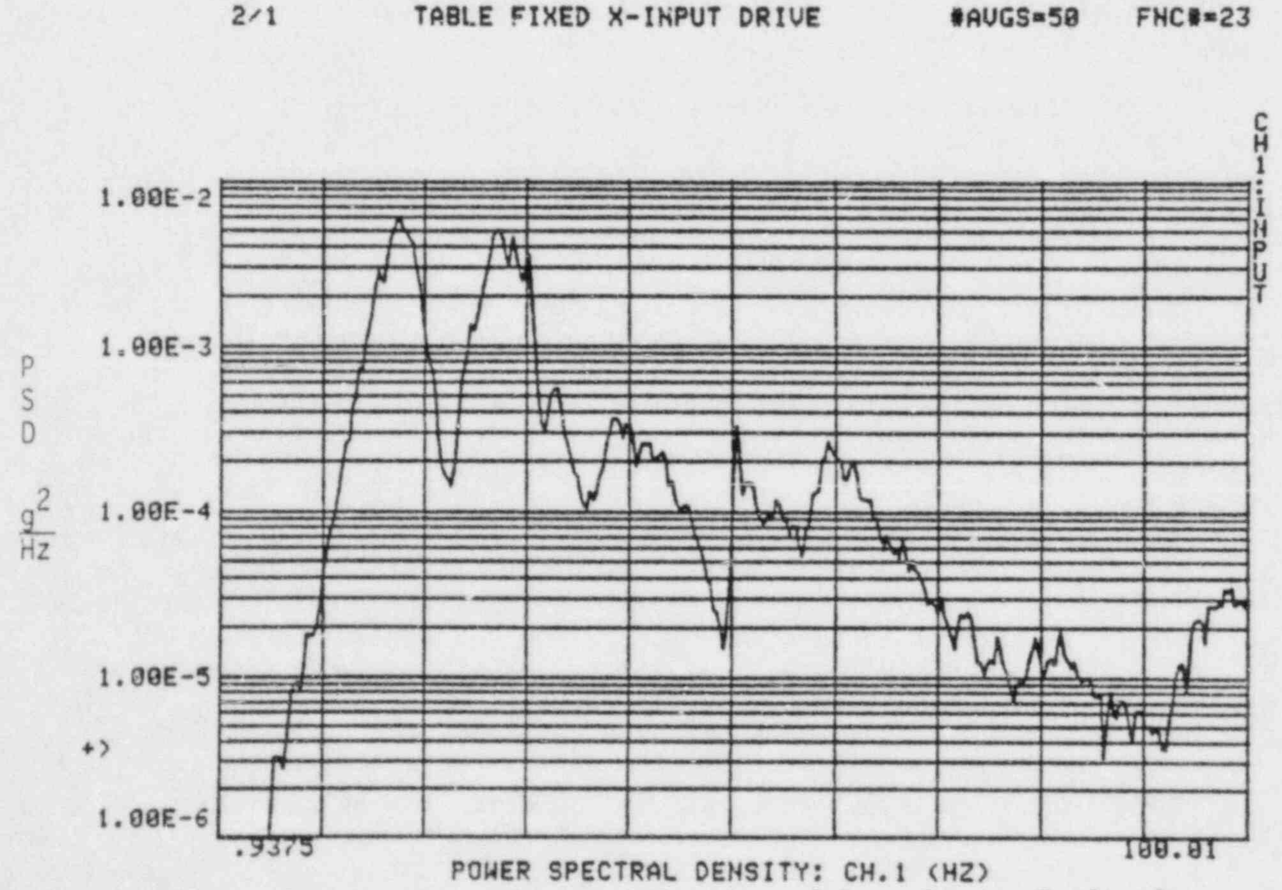


Figure 6.1-7. Power Spectral Density of Base Random Excitation With Fixed Vertical Table Mount

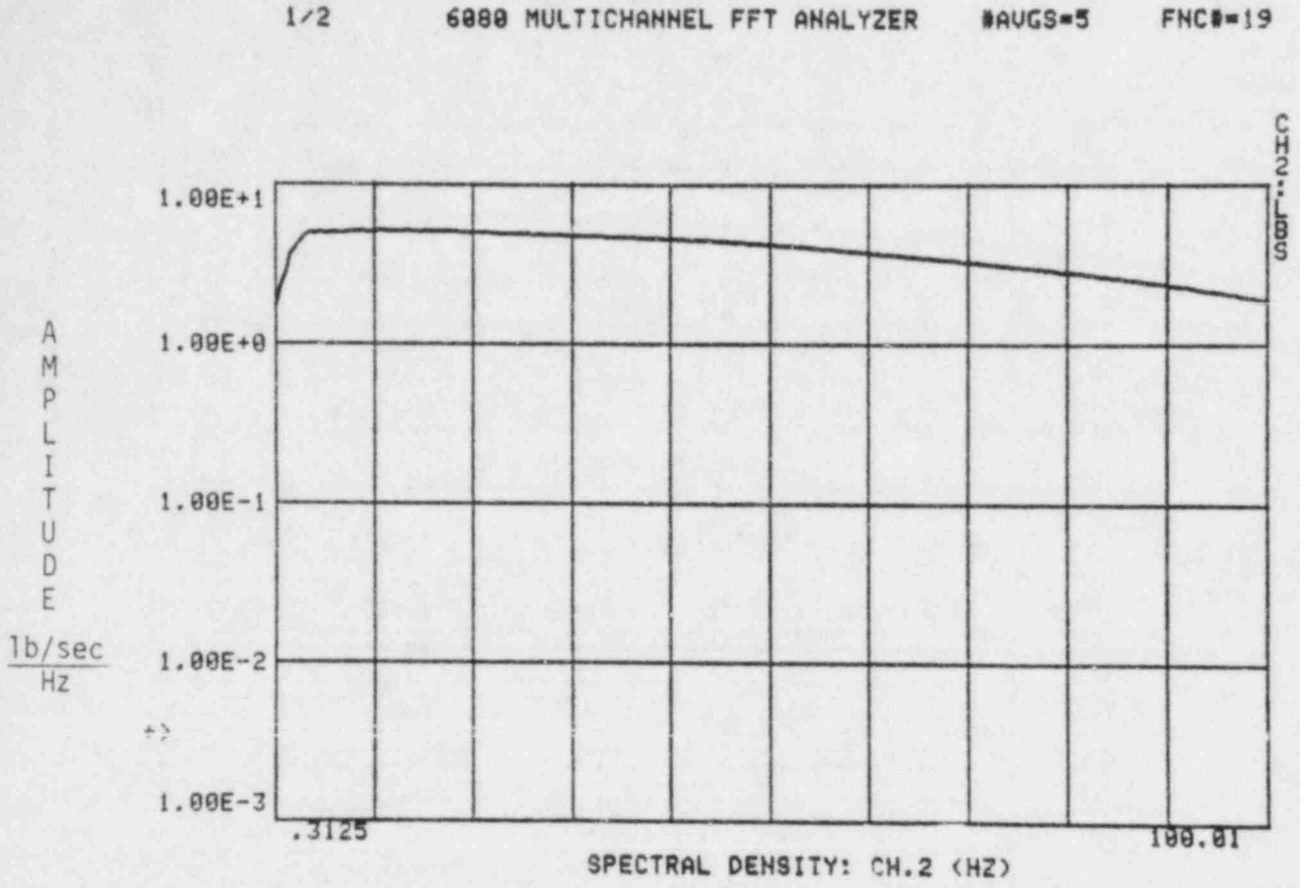


Figure 6.1-8. Amplitude Spectra of Hammer Transient Excitation With Floor Mount

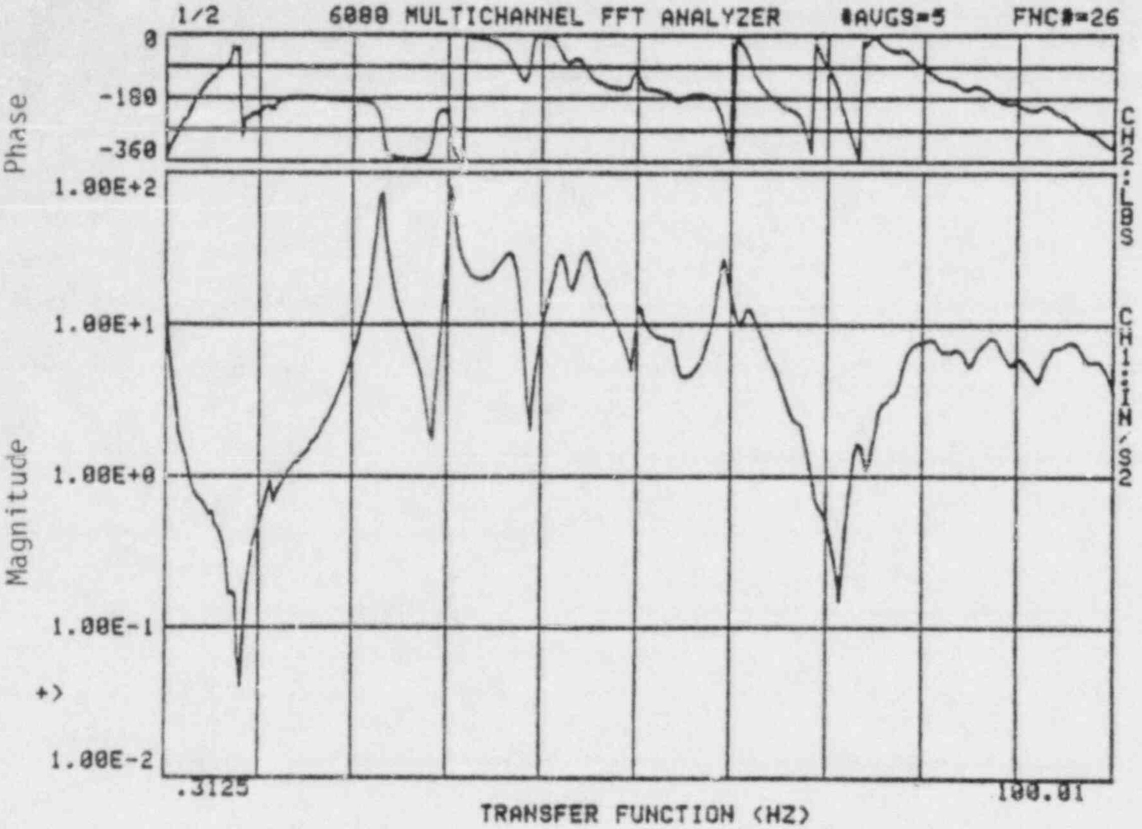


Figure 6.1-9. Transfer Function Magnitude and Phase Display for Hammer Transient Excitation With Floor Mount

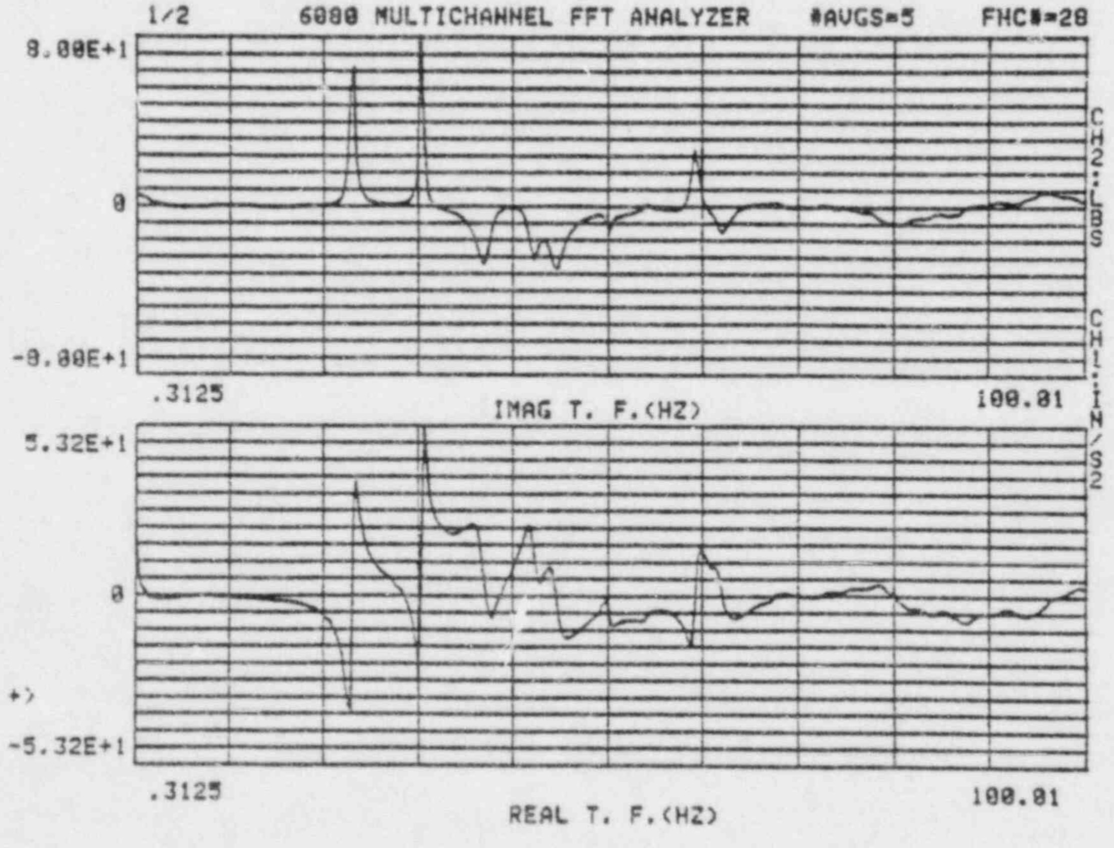


Figure 6.1-10. Transfer Function Real and Imaginary Display for Hammer Transient Excitation With Floor Mount

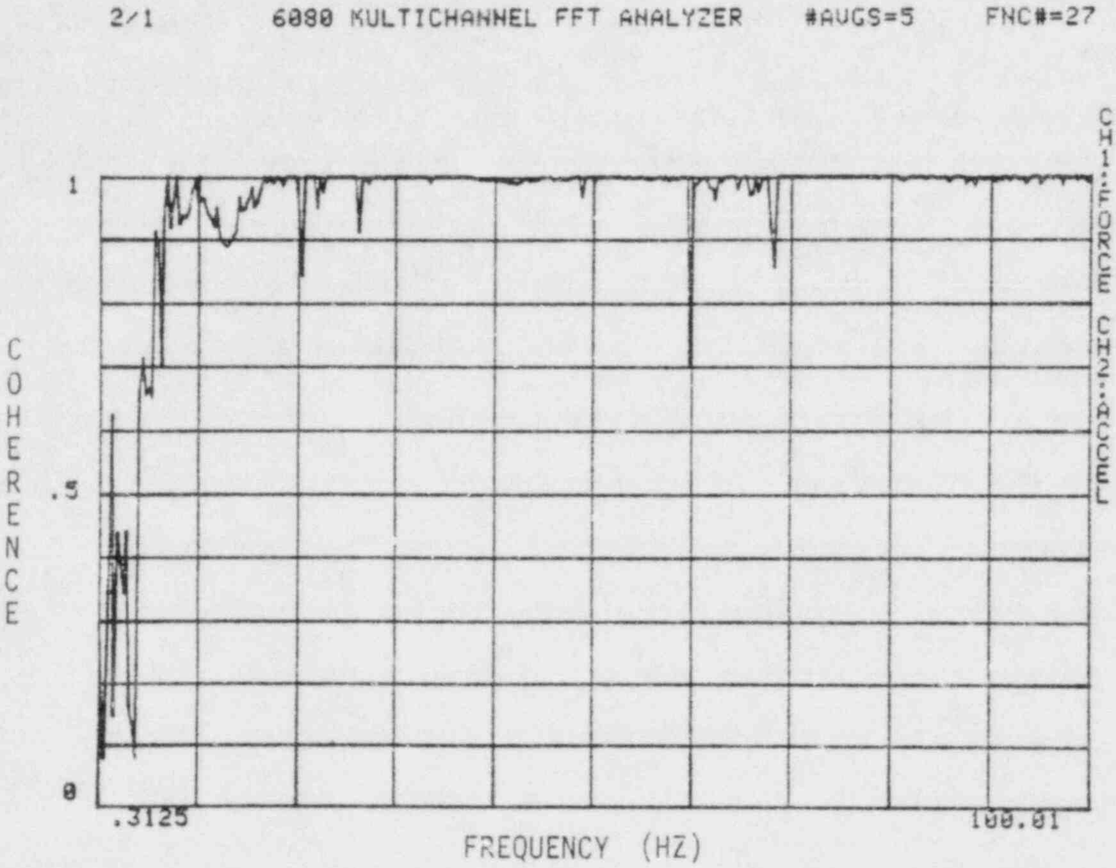


Figure 6.1-11 Coherence Between Excitation and Response at Position 5 for Hammer Transient Tests

6.1.2 Uncertainty of Boundary Conditions

All the table mounted results described to this point were for the condition with the vertical table bolted to fixed supports. This condition more closely represents the floor mounted installation. For actual earthquake simulation the vertical table must be freed to allow for biaxial excitation which will introduce additional compliance resulting from tolerances in the bearings and stiffness of the table structure and hydraulics system. An additional series of structural identification tests were performed with the table in its free condition and centered vertically. Both swept sine and random excitation testing was performed. The results for the two procedures give similar frequencies, although the amplifications are different (Figures 6.1-12 and 6.1-13).

A series of these tests were performed looking at the responses at several locations. Table 6-1 summarizes the results and compares them to the table fixed condition results. The first three modes show a significant lowering of frequency for the table free condition. The higher modes are not affected as significantly since these are primarily local instrument rack modes and are not influenced by the changes in table compliance. The first three modes, side-to-side bending, fore-aft bending and torsion of the frame, are influenced with the fore-aft bending showing the most significant shift. Preliminary thoughts on the reason for the difference in the relative amount of shift between the first two modes are centered around the interaction of the bottom plate stiffness, horizontal table stiffness, tolerances in the bearings and compliance of the hydraulics. Because of the mounting of the electrical rack on the bottom plate, the stiffness of the plate will be greater on side-to-side bending than in fore-aft bending. This in combination with the other factors would tend to result in the differences seen. Additional tests will be required to fully verify these conclusions. To insure a valid qualification program one must be assured that any frequency differences between table mounted and installation conditions will not effect the functionality of the equipment. A procedure to lessen the effect to this test item would be to increase the thickness of the baseplate. One must recognize that these differences are possible for specific specimen/table combinations.

In addition to the uncertainties associated with the compliance of the table and its effect on the qualification procedure, significant differences are possible for floor mounted conditions. The tightness of bolts holding the test item to the floor can have a noticeable effect on the frequencies and mode shapes obtained from floor mounted tests. For reasonable amounts of torque it is not necessary to repeat values exactly to obtain comparable results. The electrical rack orientation on the floor and the corresponding bolting locations had a more significant effect. For the results of this program and previous experience, uncertainties in the nature of boundary conditions can significantly alter results and make comparisons to theoretical results difficult.

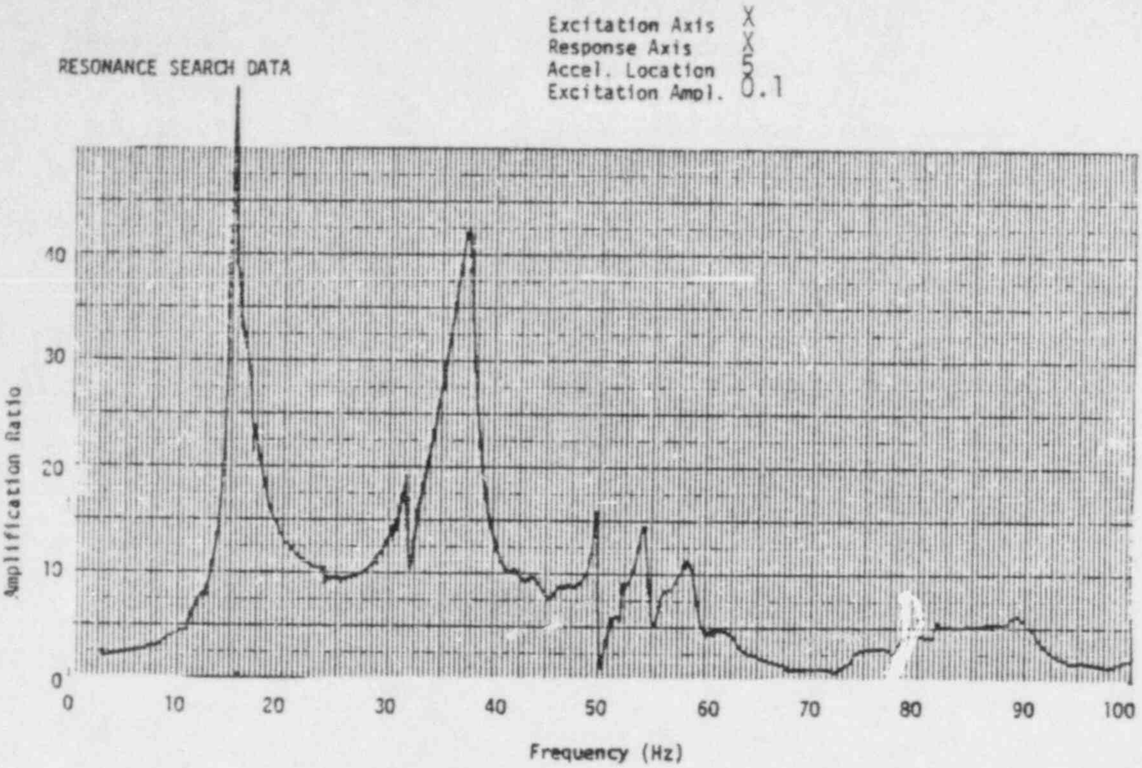


Figure 6.1-12. Position 5 Transfer Function for Sine Sweep With Free Vertical Table

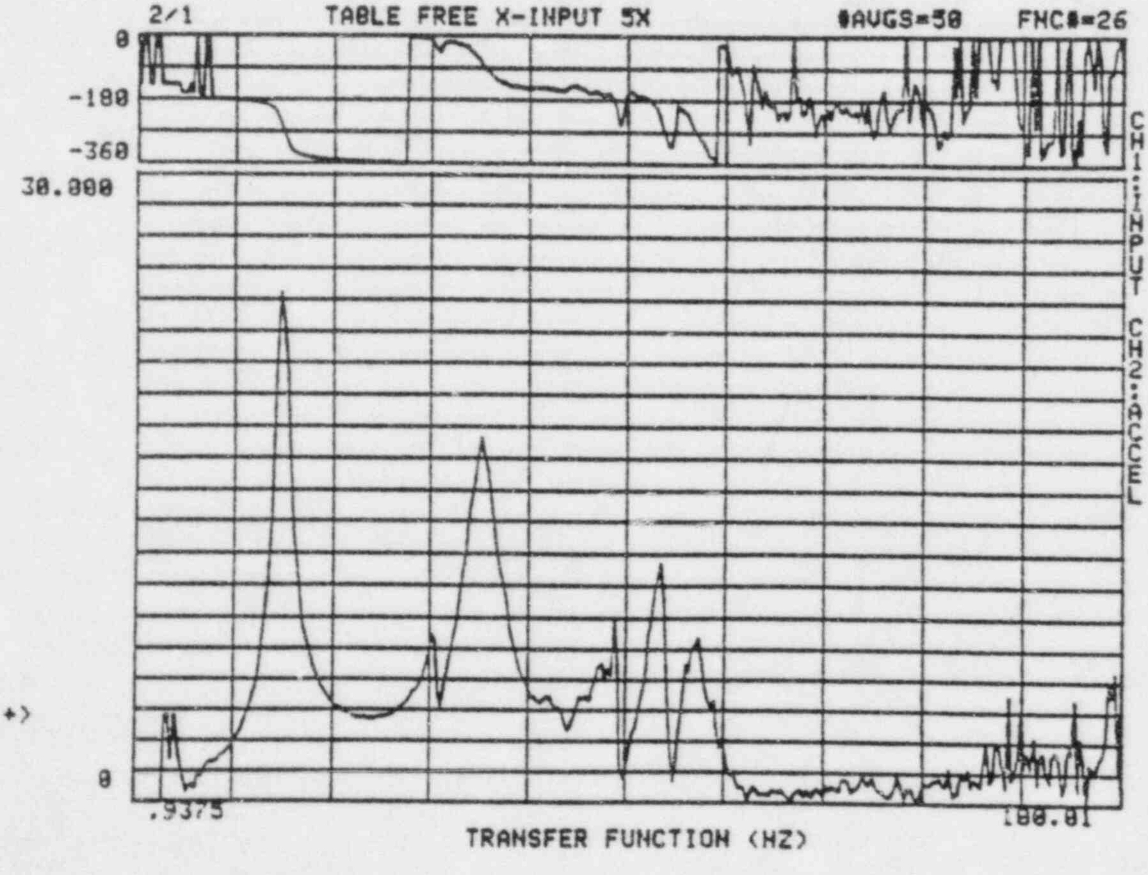


Figure 6.1-13. Position 5 Transfer Function for Random Excitation With Free Vertical Table

TABLE 6-1. TABLE MOUNTED MODAL SURVEY

Mode No.*	Table Free Frequencies (Hz)	Table Fixed Frequencies (Hz)
1	10.0	12.0
2	15.5	22.5
3	31.5	32.5
4	37.0	37.5
5	41.0	-
6	50.0	50.5
**	52.5	52.5
	54.5	54.5
	57.0 ***	58.0
	63.0 ***	62.5
	73.0 ***	72.5
	76.5	75.0
	79.0	79.5
	81.0 ***	82.0
	84.5	91.0
	90.0 ***	88.0
		94.0

* Refer to Table 5-1.

** Mode shapes on table not defined well enough to establish correlation for remaining frequencies.

*** These groups of frequencies may not correspond to each other due to limited data and complexity of higher modes.

6.2 Suitability of Seismic Waveforms

6.2.1 Ground Level

The suitability of any test time history can now be determined by means of the criteria suggested from Section 3.0. Herein this will be done in detail for some typical test runs. Generation of these waveforms has already been described in Section 4.0.

A time history and time interval RMS is plotted for horizontal excitation for Run 001 in Figures 6.2-1 and 6.2-2 respectively. The horizontal line at 0.39 g in Figure 6.2-2 denotes the 1.25 $\bar{a}_0$ level at and above which constitutes the strong motion of the event. The motion was generated such that the TRS enveloped the RRS, as shown in Figure 6.2-3. (Recall that the RRS is given by R.G. 1.60 at 1 g.) To further check the adequacy of frequency content for this signal, the PSD's of Figure 6.2-4 are presented. The R.G. 1.60 line is a PSD transformed from the RRS at 1/6 octave resolution. The similarly transformed TRS is also shown. The time history PSD was computed directly with a 1-Hz resolution. The data shows a completely adequate simulation for frequency content, with some excess above 20 Hz. The latter excess is caused by hydraulic generation of harmonic content with no input at those frequencies. Note also that a slight dip below the required PSD curve at one point occurs even though the TRS just touches the RRS. The actual computations are performed at different center frequencies so that some resolution differences occur.

Stationarity, amplitude probability, and coherence samples for the test run are shown in Figures 6.2-5 through 6.2-7. These data are very similar to that shown for the earthquakes in Section 3.0. The amplitude probability density is only approximately Gaussian, with some central concentration and a peak/RMS ratio of 5.5 for the strong motion portion of the signal. Thus, a good ground level simulation appears to have been achieved. Similar results were obtained for Runs 002, 003, 004, 011 and 012.

6.2.2 Elevated Level

In Section 3.2 the characteristics of building floor level excitations were discussed, as responses which result from ground level motions. Similar effects should occur for the instrument rack in the present case, since simulated ground level motion was imparted to it for some test runs. Thus, the hypotheses can be studied from the data taken on the rack for these runs. The transfer function for position 3 and X-Z excitation showed resonances at about 16 and 50 Hz. Thus, the response time history is amplified, as shown in Figure 6.2-8a, and the input response spectrum is amplified at the resonances, as shown in Figure 6.2-8b. Indication of frequency location of energy content is shown in Figure 6.2-9. The transformed PSD was again based on a 1/6-octave resolution. while the time history PSD is based on a 1-Hz resolution.

Further information on typical response is shown in Figures 6.2-10 through 6.2-12. The stationarity limits of the frequency content

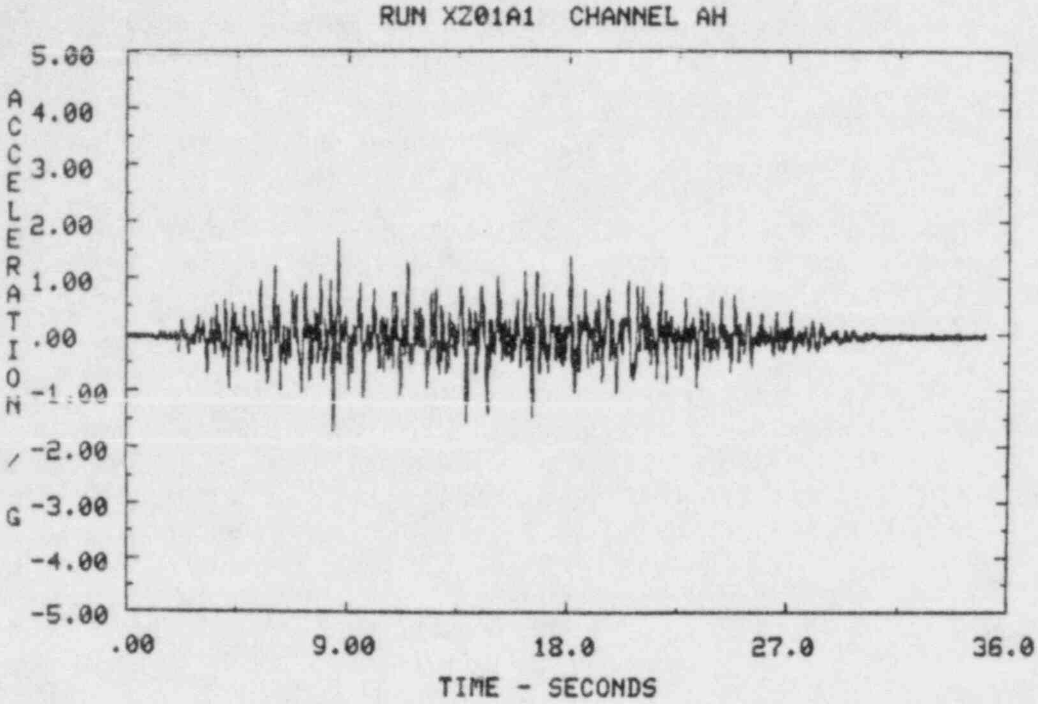


Figure 6.2-1. Horizontal Excitation Time History for Run 001

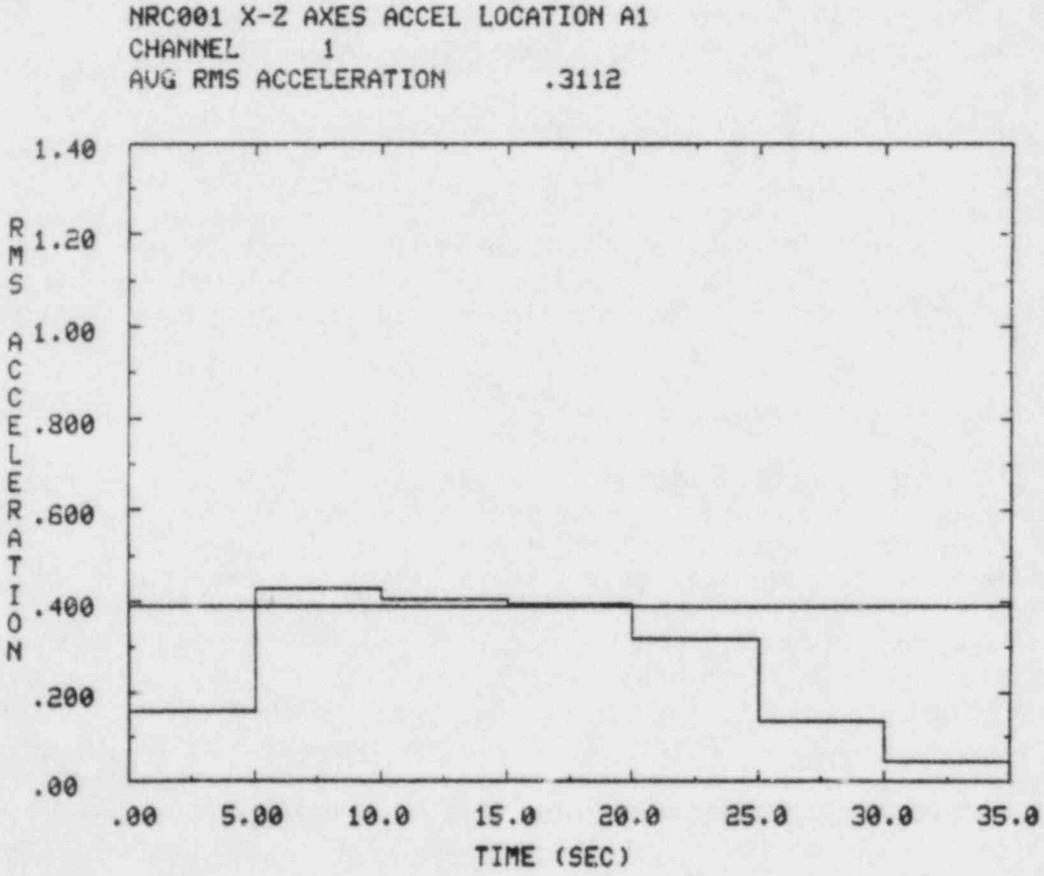


Figure 6.2-2. Horizontal Time Interval RMS Acceleration for Run 001

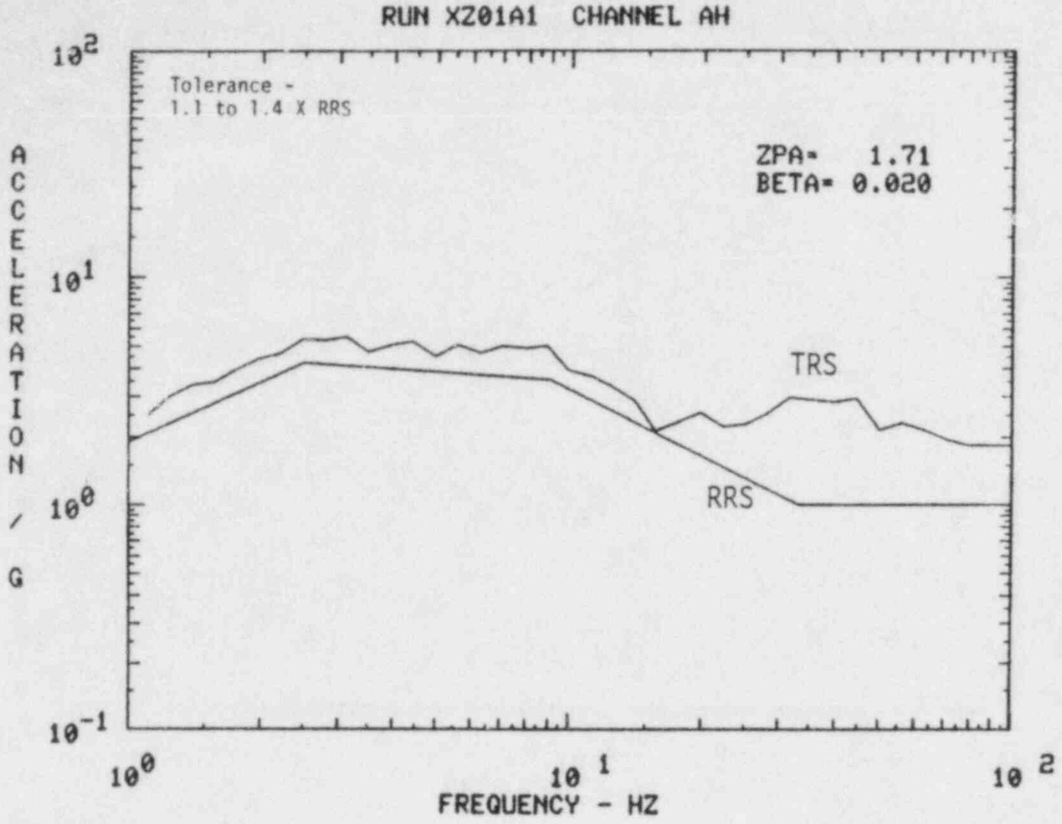


Figure 6.2-3. TRS Envelope of RRS for Run 001

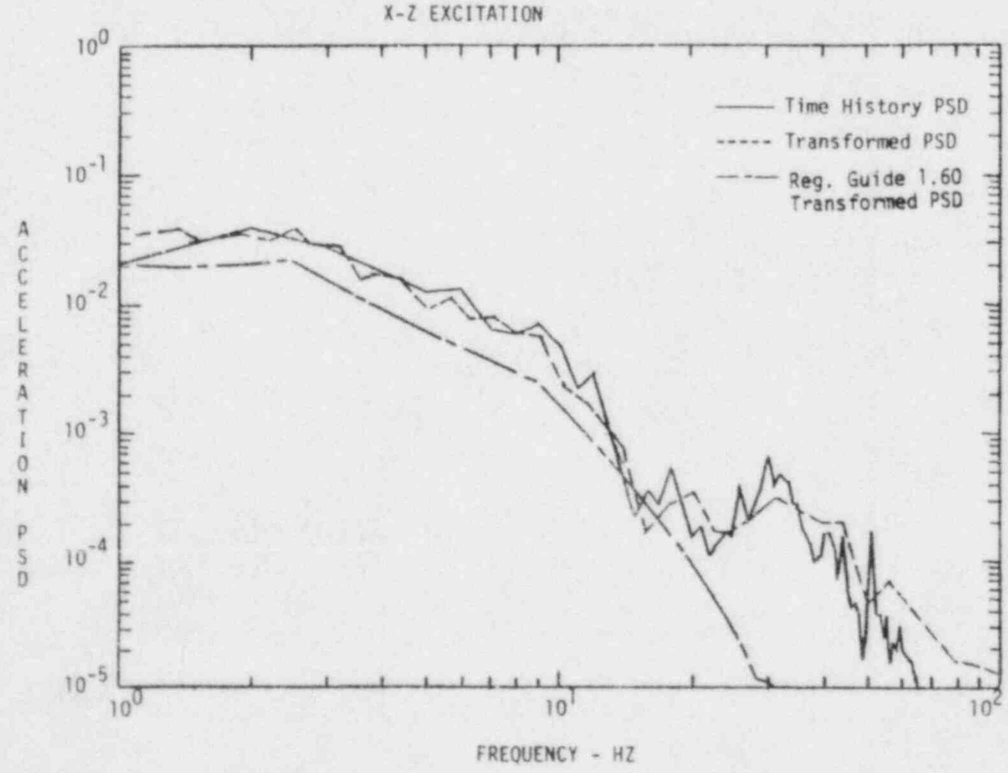


Figure 6.2-4. Comparison of PSD's for Run 001
Horizontal Excitation

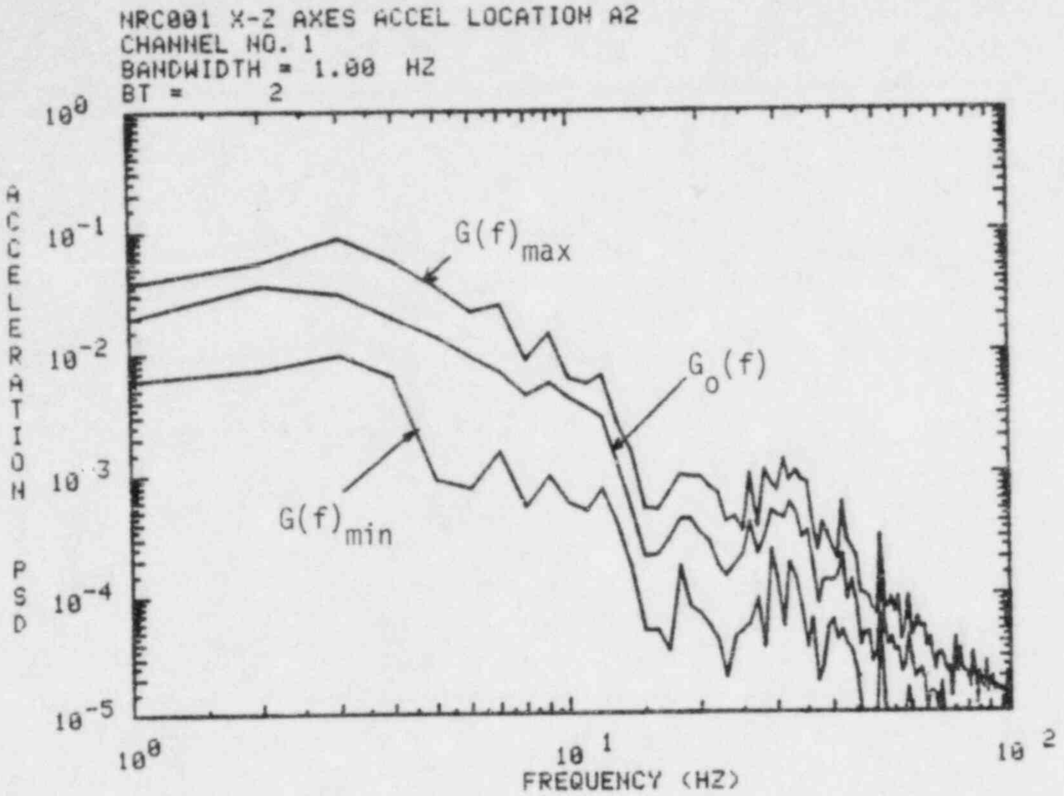


Figure 6.2-5a. Stationarity for Horizontal Run 001 With BT = 2

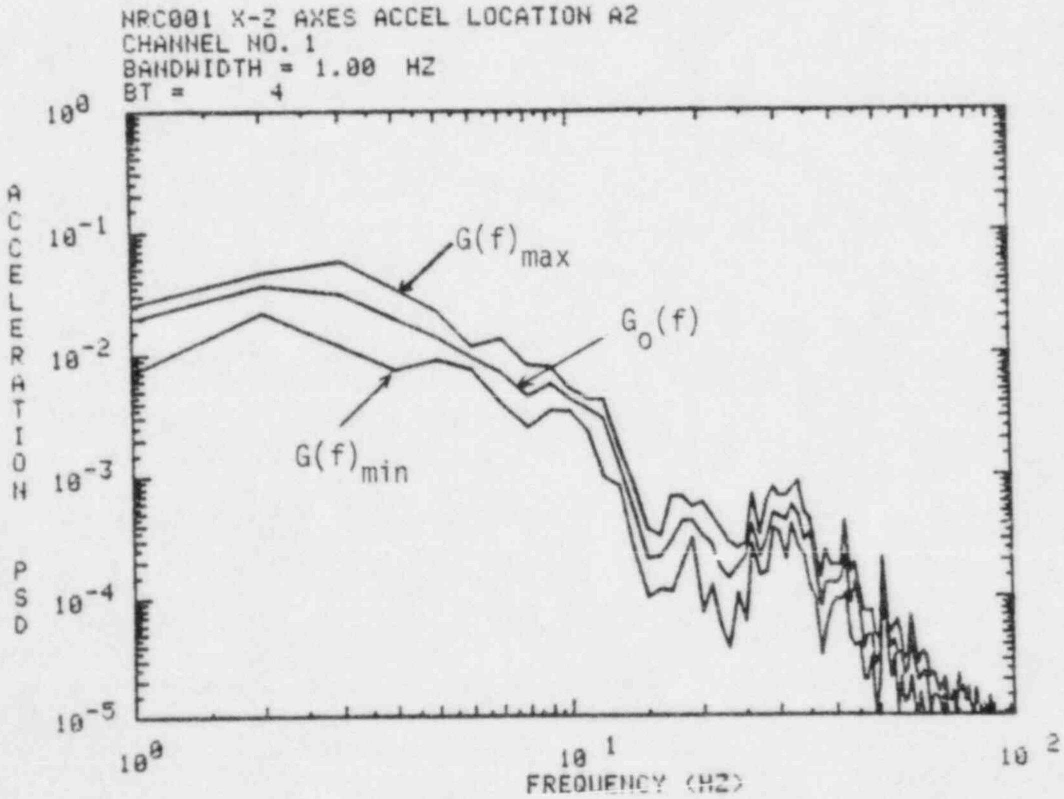


Figure 6.2-5b. Stationarity for Horizontal Run 001 With BT = 4

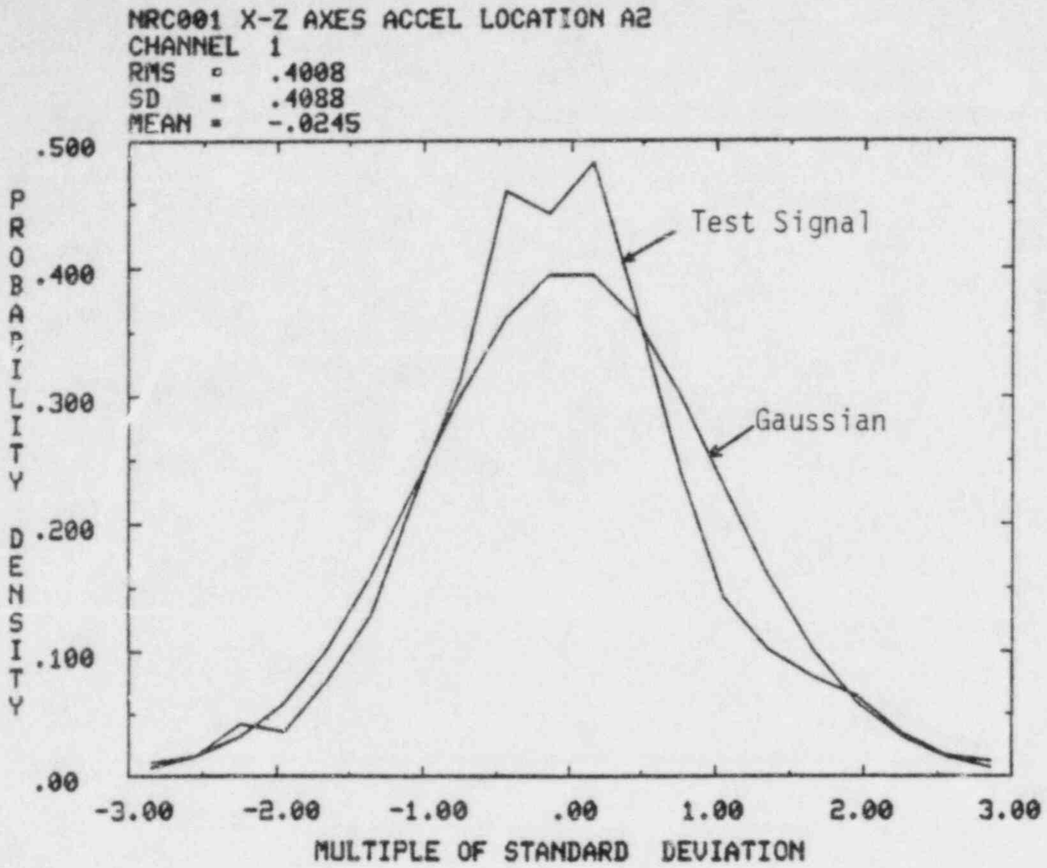


Figure 6.2-6. Amplitude Probability Density for Horizontal Run 001

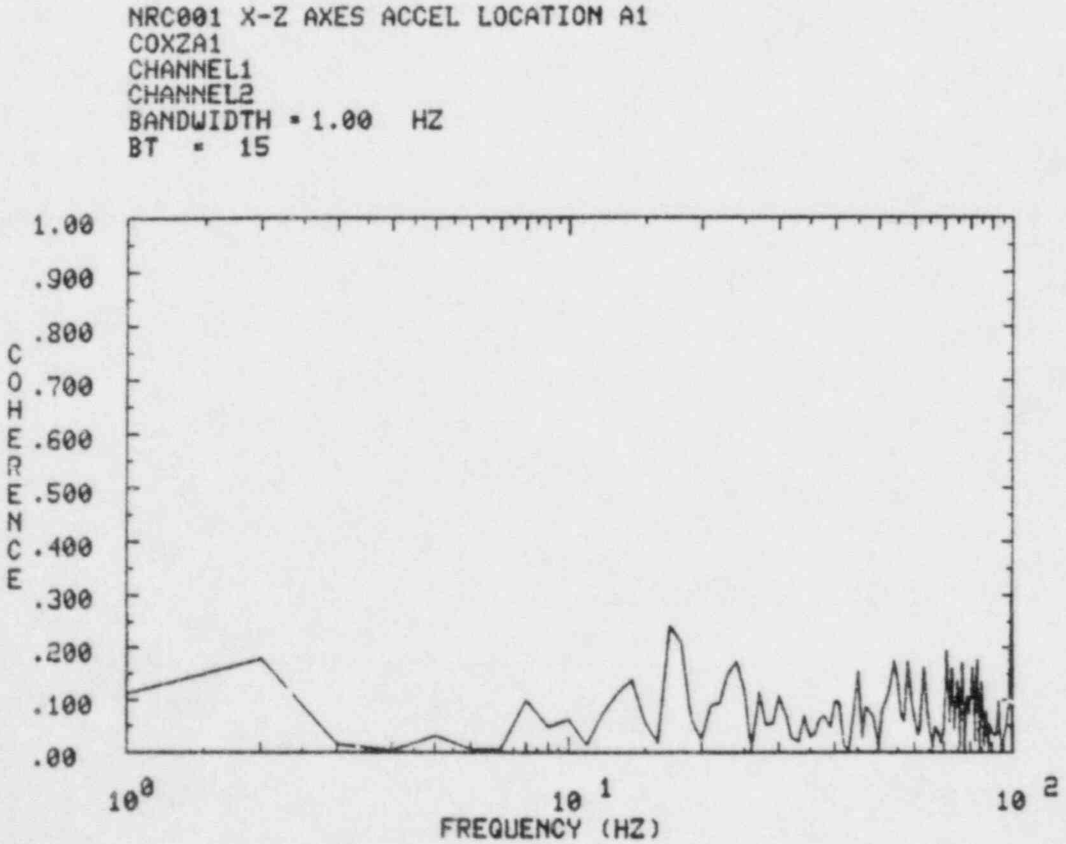


Figure 6.2-7. Coherence Between Horizontal and Vertical Run 001

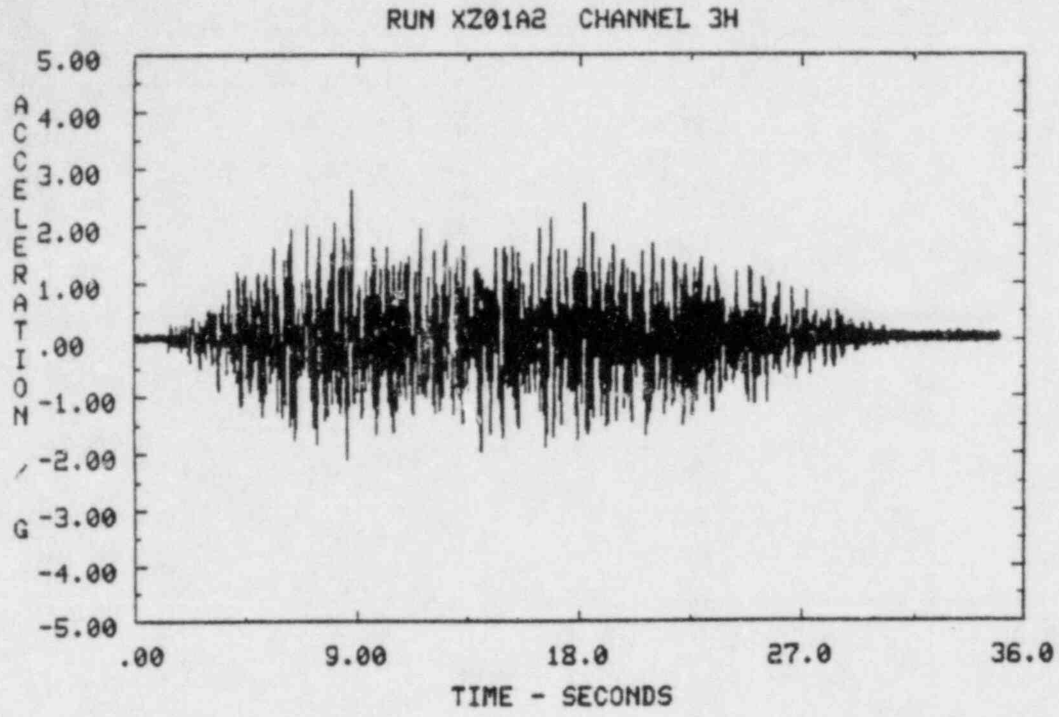


Figure 6.2-8a. Horizontal Time History for Response Position 3 and Run 001

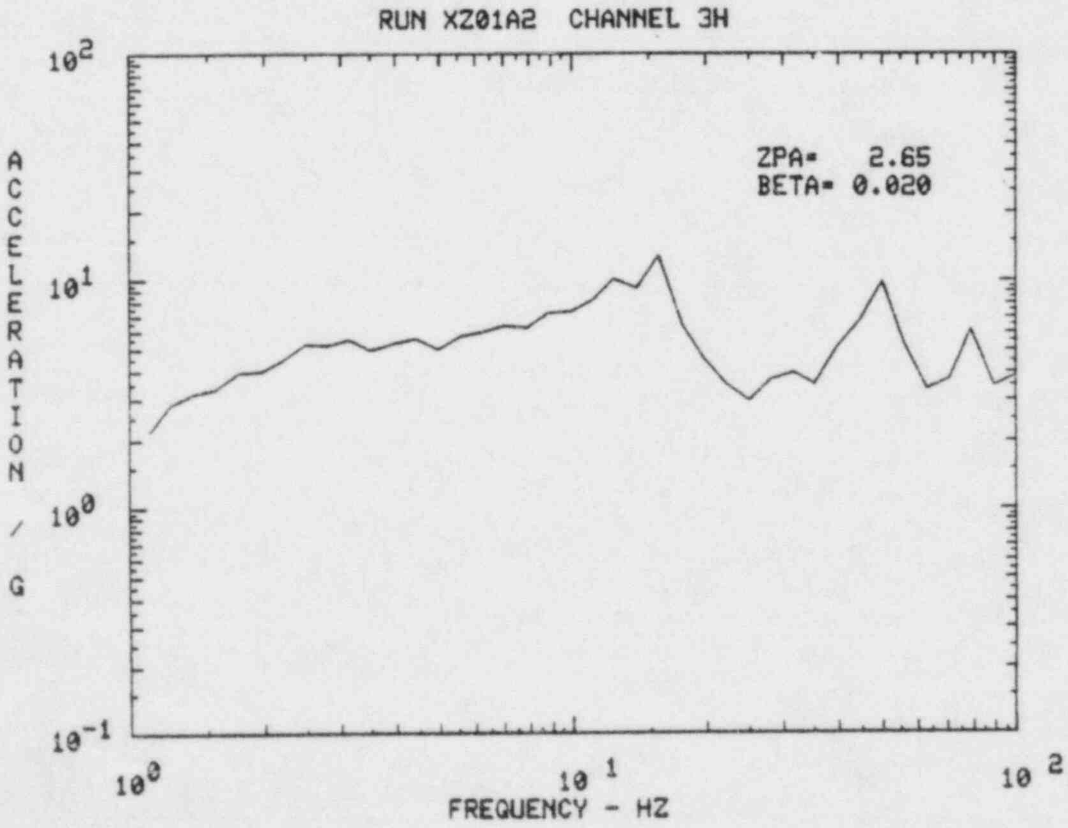


Figure 6.2-8b. Horizontal TRS for Response Position 3 and Run 001

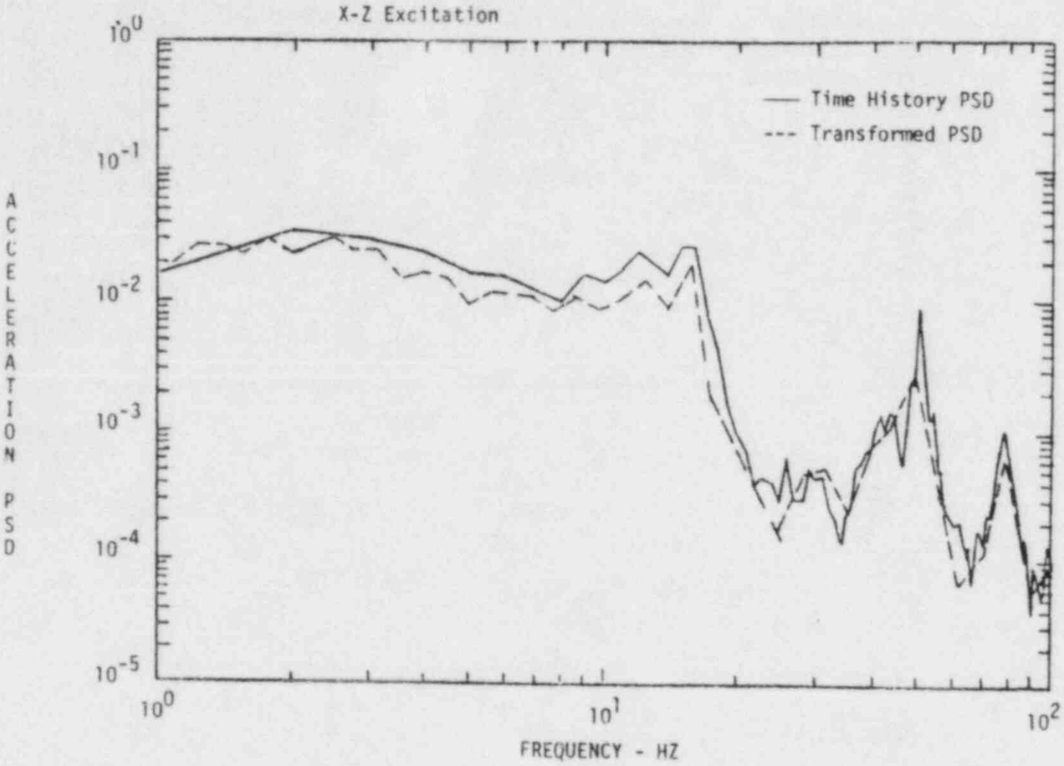


Figure 6.2-9. Horizontal Response PSD at Position 3 and Run 001

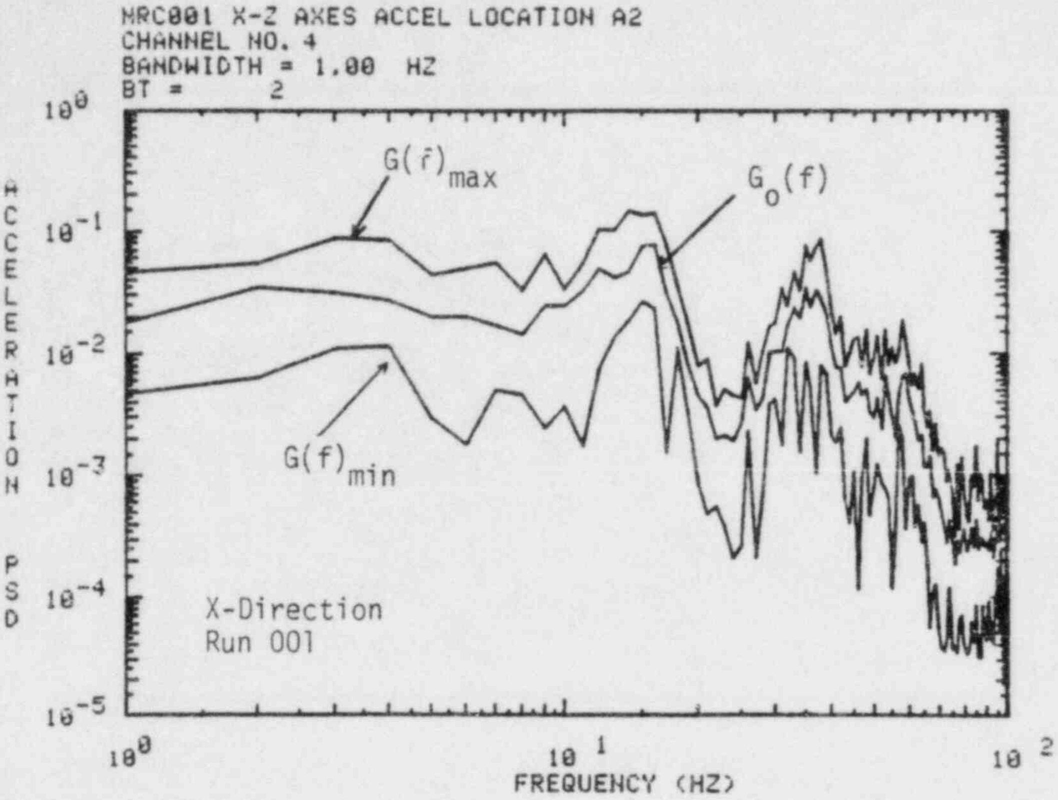


Figure 6.2-10a. Stationarity for Response at Position 5 With BT = 2

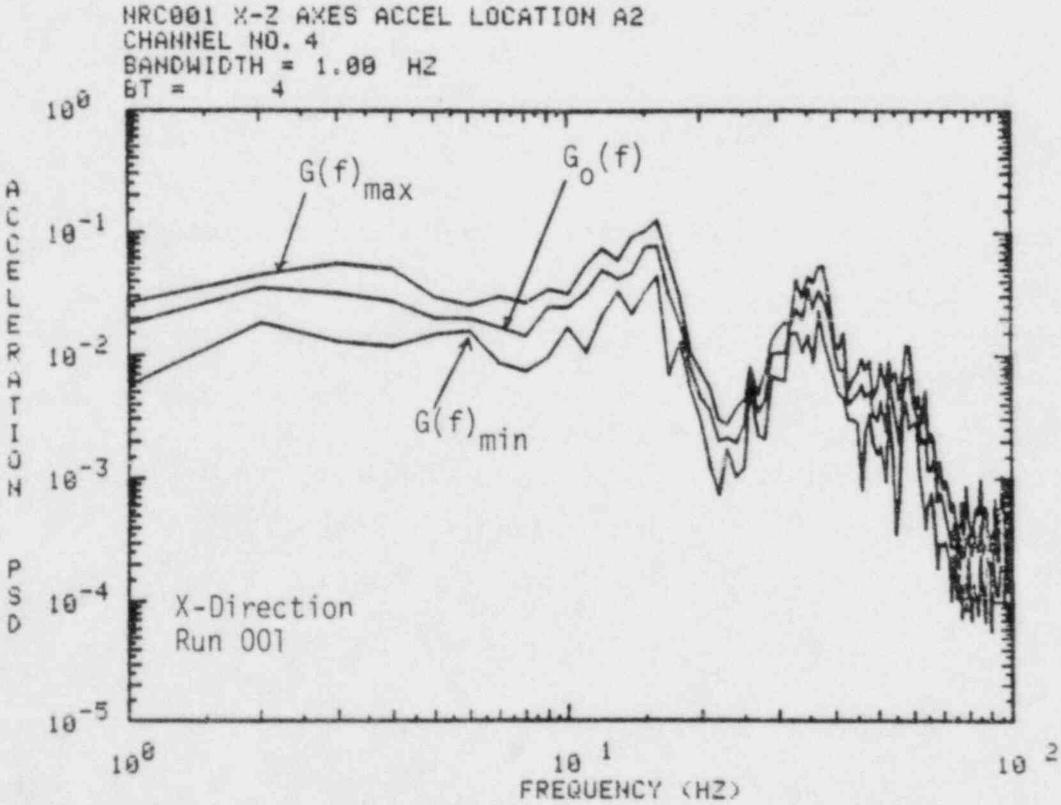


Figure 6.2-10b. Stationarity for Response at Position 5 With BT = 4

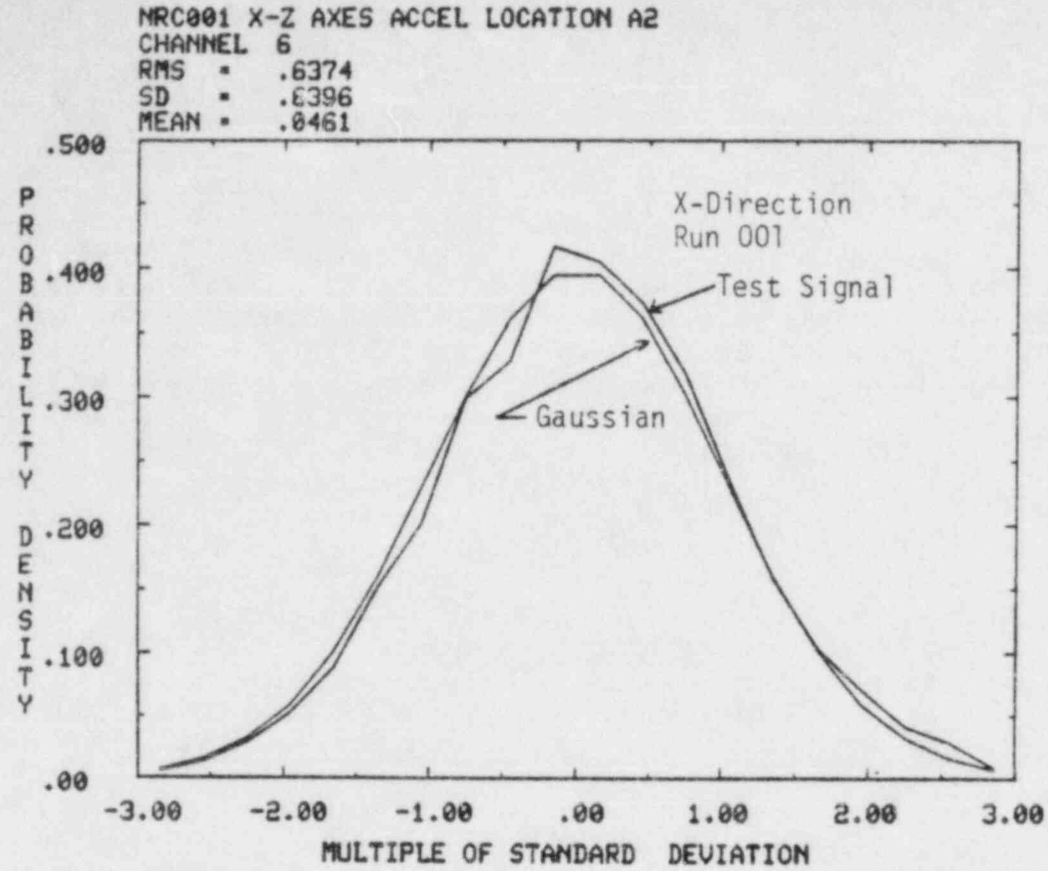


Figure 6.2-11. Amplitude Probability for Response at Position 3

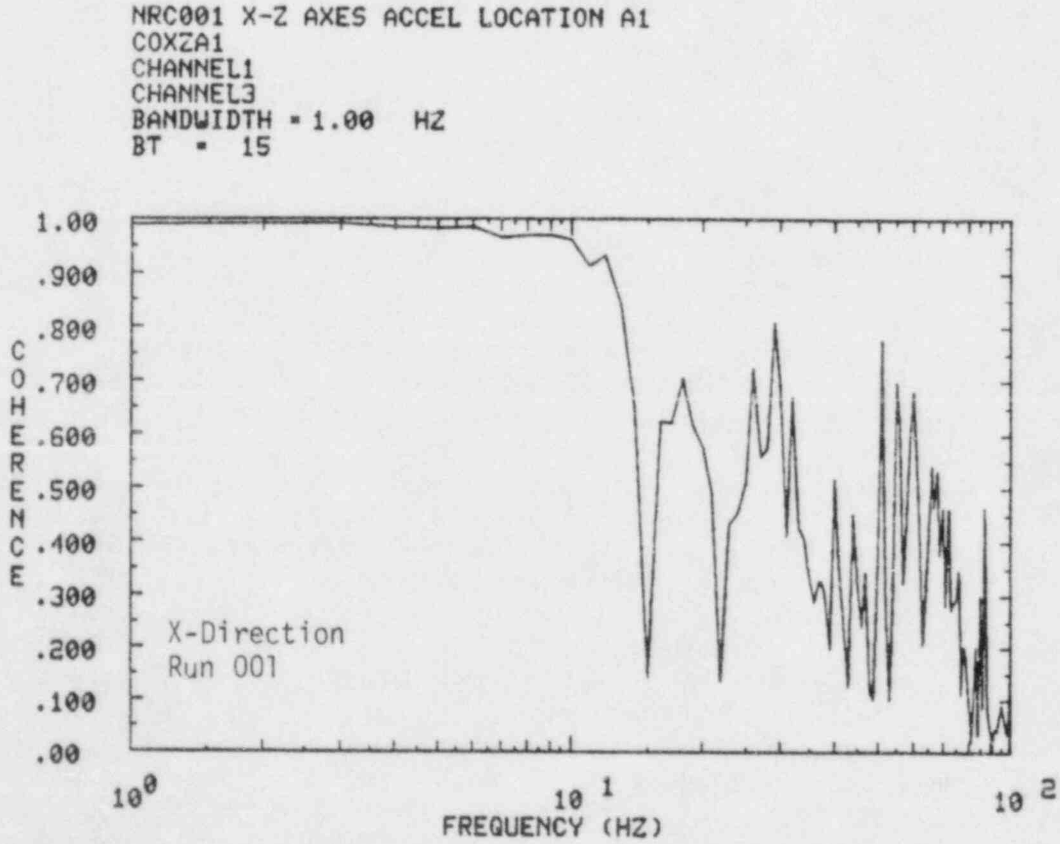


Figure 6.2-12. Coherence Between Response Position 2 and Horizontal Excitation

appear to correspond to that of the excitation, as shown in Figures 6.2-5. Furthermore, amplitude probability density of the response at position 3, as shown in Figure 6.2-11 is closer to true Gaussian than the excitation. In Figure 6.2-12, the coherence between a response and the excitation is high, as would be expected for a linear system, until it becomes irregular above 12 Hz. The latter behavior occurs since the excitation falls off rapidly above 12 Hz (see Figure 6.2-4) and the effects of other noise sources become more effective compared with the input. These data tend to support the hypotheses set out in Section 3.2.

6.3 Accuracy of Response Spectrum Envelope

To look at the potential effect of response spectrum enveloping accuracy on qualification validity, three levels of toelrances were defined for two sets of earthquakes. The two earthquake sets were: the standard R.G. 1.60 RRS, (Figure 6.3-1) and an extended R.G. 1.60 RRS with additional energy between 9 and 20 Hz (Figure 6.3-5). The three sets of tolerances included: (1) normal tolerance AMIN = 1.0 and BMAX = 1.4, (2) close tolerances AMIN = 1.05 and BMAX = 1.15, and (3) no tolerance in which excessive low frequency energy was supplied with no energy input above 10 Hz. The run numbers used to define these six conditions are:

	R.G. 1.60 Run No.	Extended R.G. 1.60 Run No.
Normal Tolerance	001	002
Close Tolerance	003	004
No Tolerance	005	006

In all cases, including 005 and 006, the TRS was required to envelope the RRS. The tests were run for both X-Z and Y-Z biaxial excitation.

When one considers the level of tolerances required, the time associated with the development of the time history test signals must also be considered. The time between the initiation of the signal development process on the computer to the time of the first test run on the test specimen may take between two to four hours. This depends on the complexity of the RRS and the amount of interaction between the table and test specimen. A typical time for the development of Runs 001 and 002 was three hours. An additional hour was required to obtain the desired accuracy for Runs 003 and 004 with several additional preliminary runs required to obtain the close tolerances. If fatigue of the test specimen is important, these additional runs may not be justified. In addition, if two levels are required, it is much more difficult to step up with the close tolerances and still envelop the curve on the first run because of the non-linearities of the drive. The times to develop Runs 005 and 006 were close to those of 001 and 002. It must be recognized the the above-cited synthesis times would be much larger (i.e., x 4) if manual analog manipulations were employed in our laboratory.

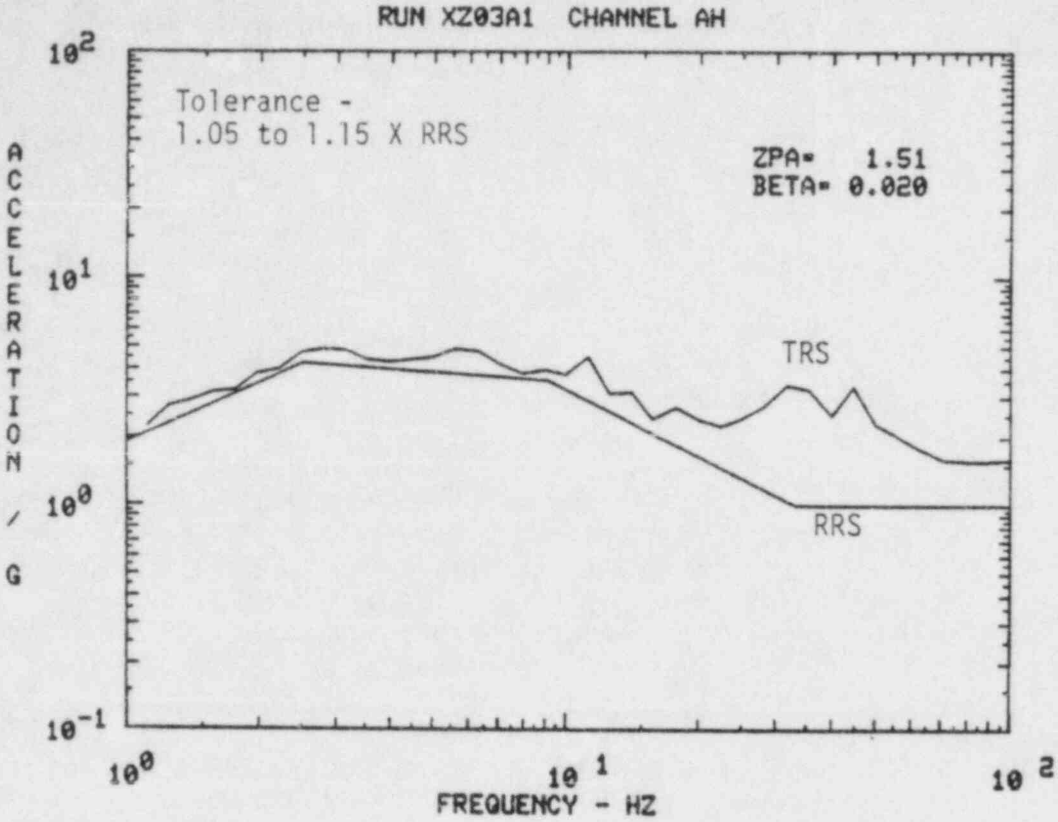


Figure 6.3-1. TRS Envelope of RRS for Run 003

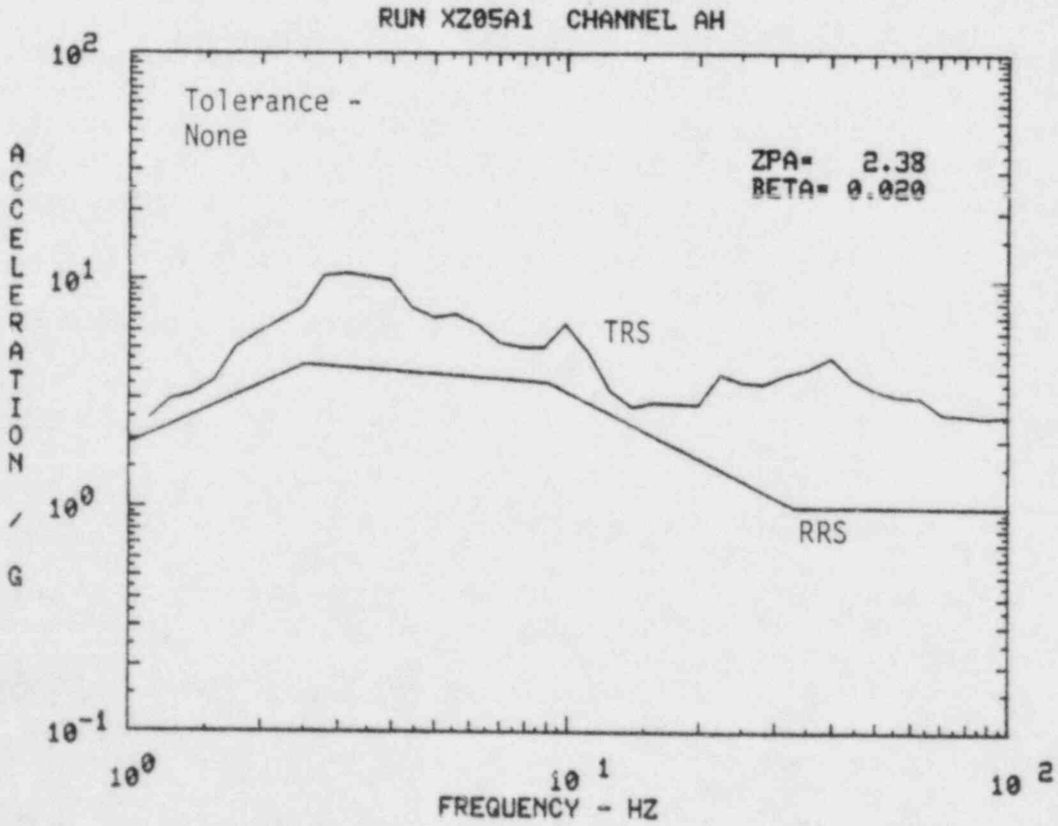


Figure 6.3-2. TRS Envelope of RRS for Run 005

As in previous sections, only representative samples of the data will be shown. Similar results were noted for other accelerometer locations and horizontal axes of excitation. The vertical results were dominated by rigid body response at elevated positions so only horizontal results are presented.

There were only minor differences between the results obtained for Runs 001 and 002 and those for Runs 003 and 004. The response at elevated positions showed the 15% difference in the mean level of the TRS indicative of the differences in AMIN and BMAX. Some indications on the resulting effects on functionality of the test items will be discussed in Section 7.0. A comparison of Runs 003 and 004 to Runs 005 and 006 for X-Z excitation is given in Figures 6.3-1 to 6.3-8. For the R.G. 1.60 earthquake the horizontal table TRS for Runs 003 and 005 are given in Figures 6.3-1 and 6.3-2 respectively. The overall level of the 005 TRS is higher with a ZPA of 2.38 g's compared to 1.51 g's for Run 003. This is a 58% increase in ZPA levels which can be considered significant. If one looks at the PSD's (Figure 6.3-3) of the input, one can see that although the TRS spectra both envelope the RRS, the PSD for Run 005 does not envelope the PSD obtained by transforming the RRS (see Section 2.3). Between 12 and 17 Hz the PSD falls below the line while in the low frequency range, below 10 Hz, the 005 PSD is significantly higher than the 003 PSD. The effect that this variation in input levels has on the response of an elevated position can be seen in Figure 6.3-4. In the region where the test PSD falls below the required PSD, Run 003 shows a significantly higher response than Run 005. The low frequency region for Run 005 is higher than Run 003 as would be expected. These differences may have a noticeable effect on the functionality of instrumentation at this location with the influence dependent upon the failure plane associated with the instrument. Similar results are evident when comparing Runs 004 and 006 (Figures 6.3-5 to 6.3-8). Because of the extended frequency requirements more of the curve for Run 006 falls below the required PSD. In attempting to envelop the RRS difficulties were encountered due to the fact that no energy was input above 10 Hz. To lift the region from 13 to 20 Hz up in Figure 6.3-6 would have required a significant amount of additional low frequency input. It was felt this was not justified since the ZPA was already 25% higher. These results demonstrate the effect the response spectra anomalies, Section 1.2, may have on the qualification of equipment. They also demonstrate that the PSD is much more sensitive than the response spectrum as a parameter for measuring the proper energy content of a simulated earthquake motion.

6.4 Limitations of the Analytical Model

All modeling is an approximation of the actual structure in question. The level of the approximation is dependent on a number of factors. Two of these are the time and money available for the development of the model. Finite element procedures for the development of linear and non-linear materials and elements in conjunction with solution procedures for any time history of loading allow for the solution of almost any physical problem. The task of the engineer is to make a judgement as to the level of approximation required to obtain the desired information.

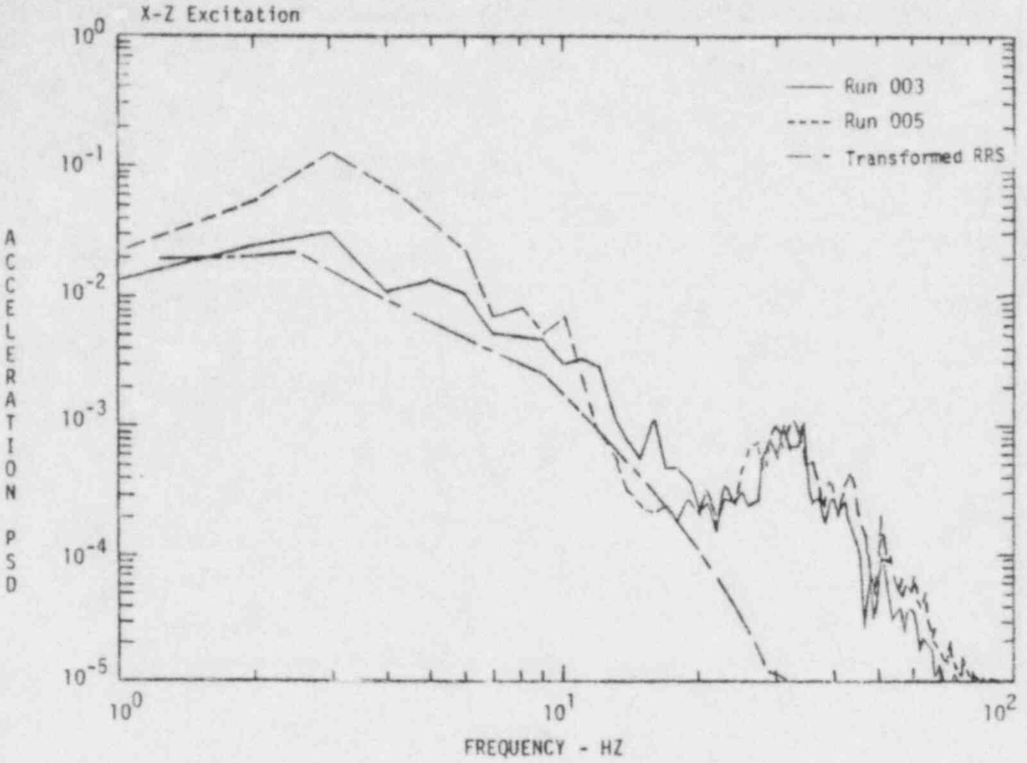


Figure 6.3-3. Comparison of PSD's for Horizontal Excitation With Different Runs

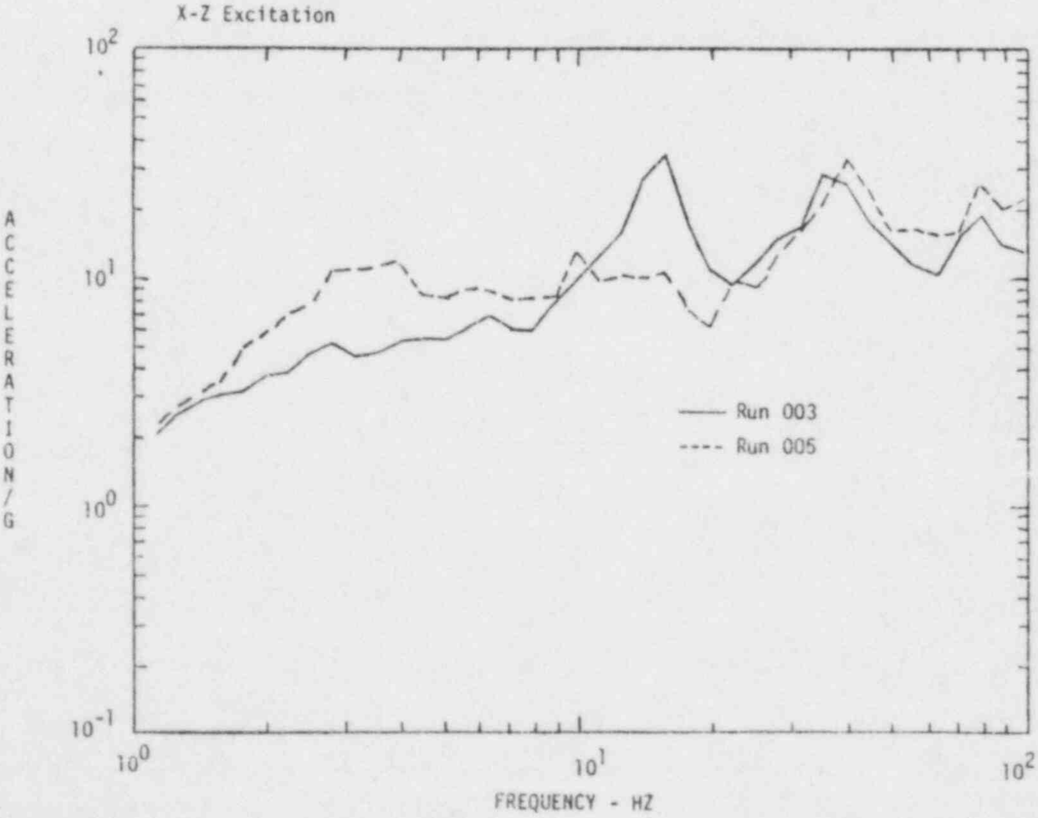


Figure 6.3-4. Comparison of Response Spectrum at Position 5 for Different Runs

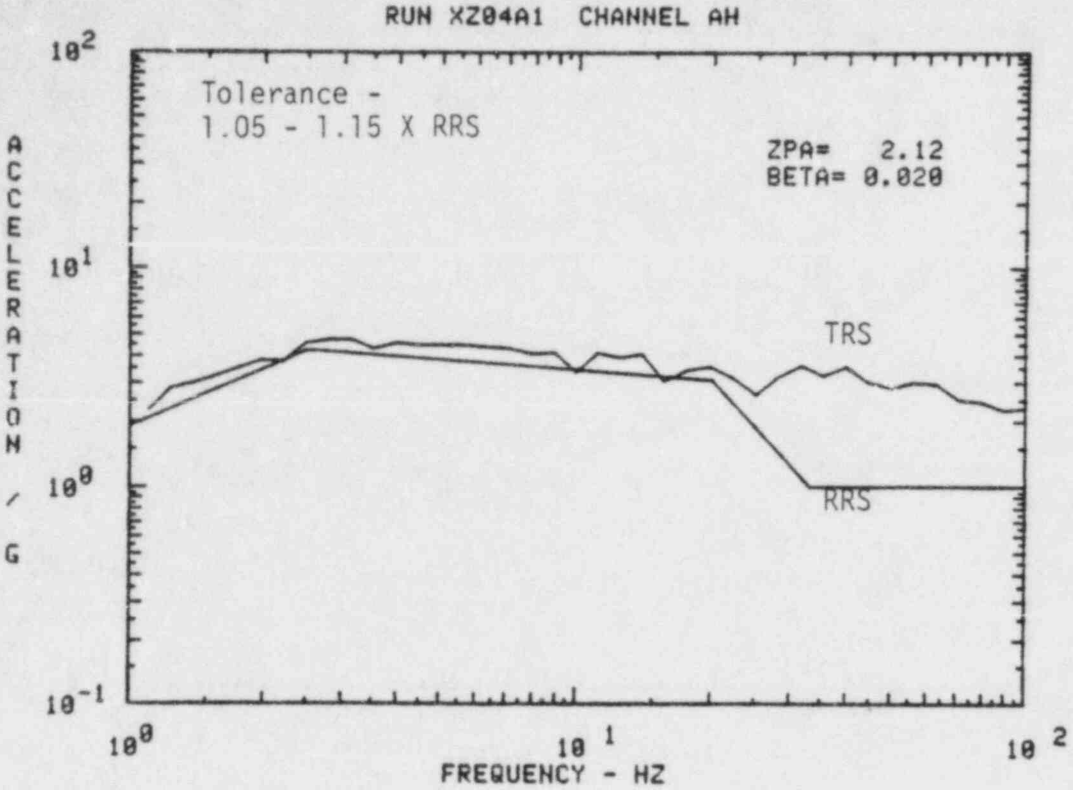


Figure 6.3-5. TRS Envelope of RRS for Run 004

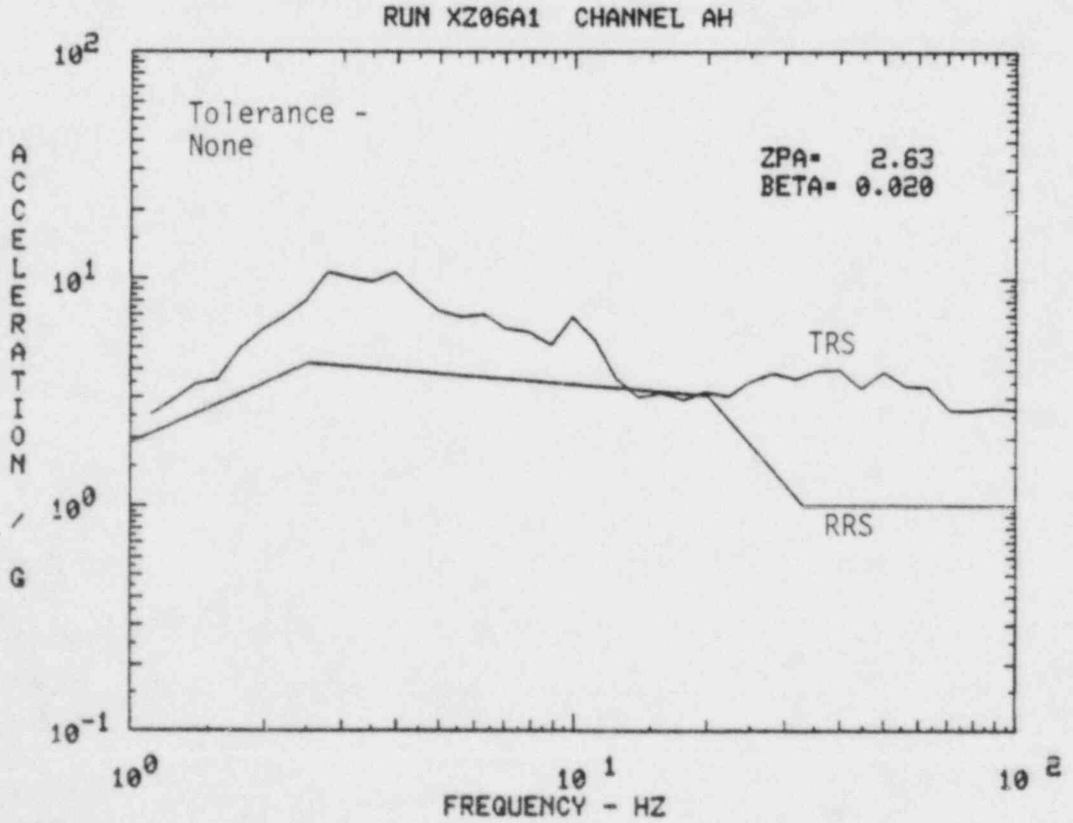


Figure 6.3-6. TRS Envelope of RRS for Run 006

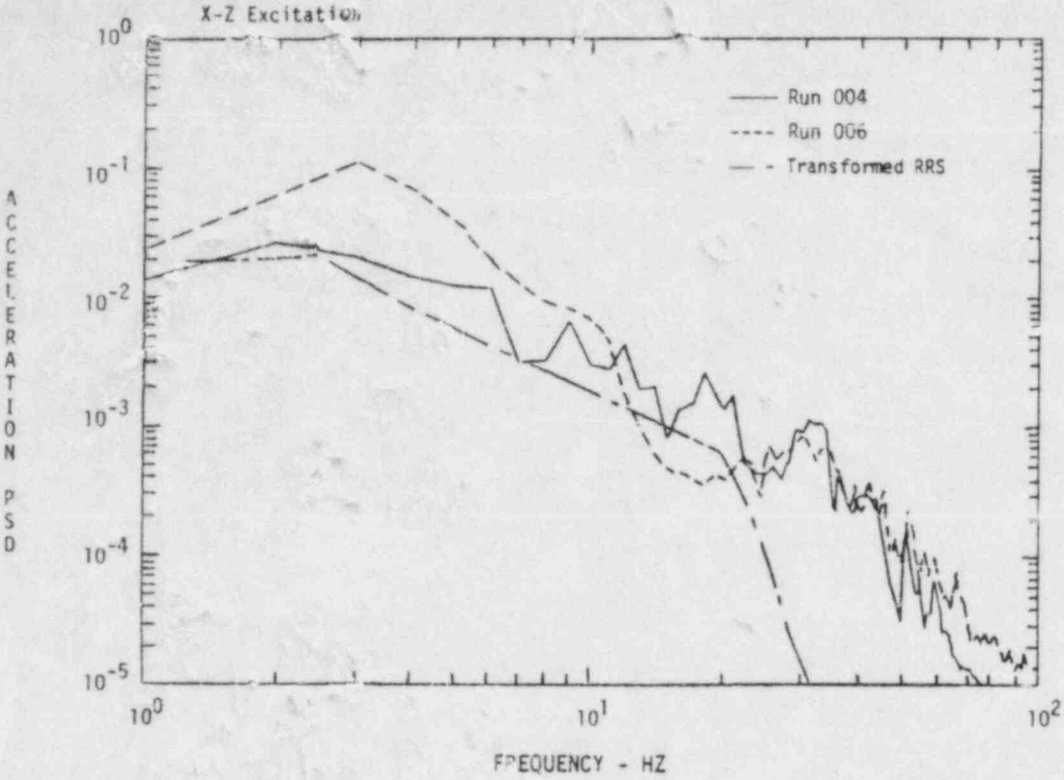


Figure 6.3-7. Comparison of PSD's for Horizontal Excitation With Extended Frequency Runs

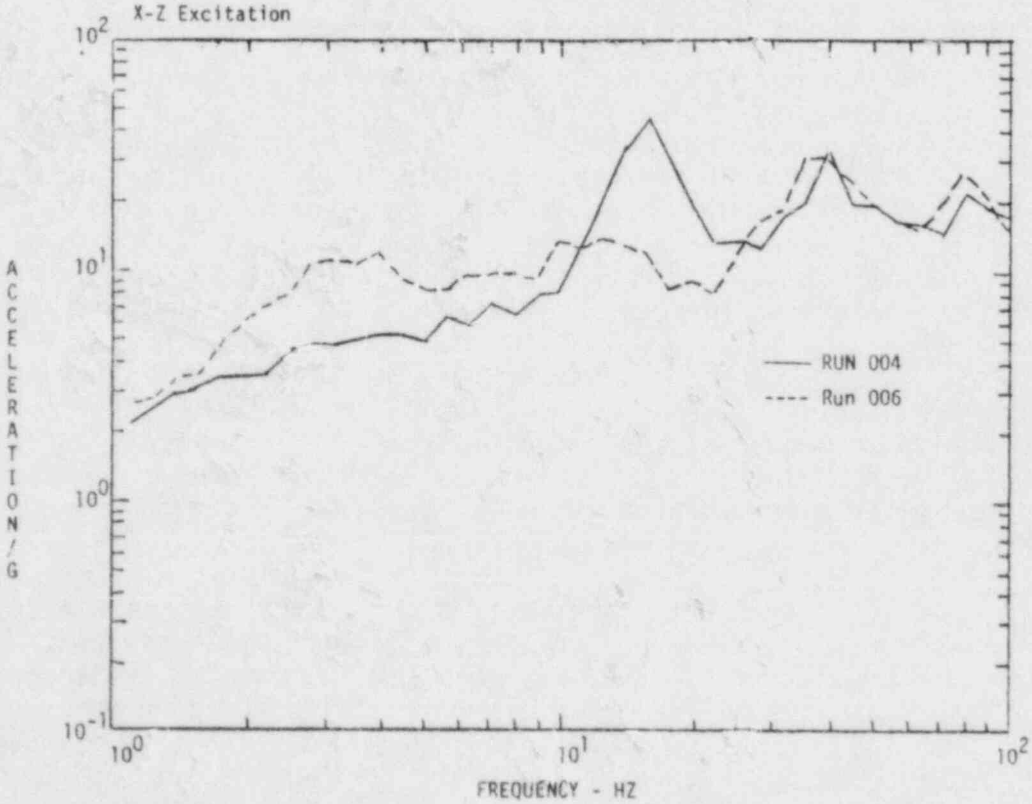


Figure 6.3-8. Comparison of Response Spectrum at Position 5 for Extended Frequency Runs

6.4.1 Adequacy of Model Synthesis

One of the main restraints on the development of any model is the documentation available describing the structure. In most instances models are developed from blueprints of the structure, as in this case. This documentation must include information on all dimensions, structural members, type of welds or connectors, material properties and location, weight, cg, inertia and physical characteristics of any instrumentation mounted on the structure. In addition, if the functionality of the item is to be determined analytically, information on the fragility function (see Section 7.0) of each instrument would be helpful. Using this information, and where possible physical measurements of the actual item, the engineer can develop an analytical model.

In Section 5.1 a description of the procedure used for the model synthesis was given. One of the first concerns was the distance between nodes required to obtain information up to 100 Hz. The final number of nodes was based upon this and practical restraints on the size of the model. The larger the number of nodes, and therefore DOF, the more costly and time consuming the analysis will be. It was felt that the model described would provide an adequate representative of the dynamic characteristics of this electrical rack up to 100 Hz. This is based on engineering judgement and no studies were performed to definitively prove this.

In typical modeling procedures, all joints are assumed to be perfectly rigid and capable of transmitting three translations and three rotations. For this model all locations where structural members were joined were assumed rigid except the boundary conditions on the bottom rectangle which were allowed to rotate about their length. Unless plate or solid elements are used to represent each leg of the angle or channels, this is the only reasonable approximation that can be made. Since the majority of connections were welded this approximation is better than would be epected for bolted or riveted connections.

One major approximation made was the stiffness of the instrument/support plate combination. The stiffness of the actual instruments or dummy weights is difficult to approximate and will depend greatly on how they are attached to the support plate. In this model this combination was modeled to only have axial stiffness and add no bending or torsional stiffness to the UNISTRUT members.

A number of approximations are also made in the development of the mass matrix. The mass of the instruments and dummy weights are a significant portion of the total mass of the model. All added masses were lumped at node points which did not necessarily correspond to the cg of the instrument. In addition, only translational, no rotational masses, were added. Both of these would tend to reduce the amount of coupling which the model could represent. To more adequately model this response it would be necessary to define node points at the various cg's and use "rigid" beams to connect these points to the existing nodes. It was felt that this additional complexity was not required.

One of the major factors on the adequacy of the model system is a definition of the boundary conditions. For this case the boundary was defined as the welded attachment of the bottom rectangle to the one inch thick steel plate. The plate, which was not included, was then "assumed" to be perfectly rigid. If more detailed information on the floor mounted case were required, it would be possible to include the baseplate in the model. Then the problem becomes modeling the bolted attachment to the floor and the non-linear effect of lifting of the plate away from the floor. If in addition the table mounted results were desired, it would become necessary to model the complete table structure and hydraulic system. In most cases this additional complexity is not required.

All of the approximations described above are necessary to develop the finite element model of the structure. The model can then be used to obtain solutions for a static load or an eigenvalue analysis. If results for a dynamic load are required, it is also necessary to specify the damping characeristics of the structure. This cannot be determined analytically and should be specified or obtained from experimental testing.

6.4.2 Functionality

The model described in Section 5.1 was designed to represent the structural characteristics of the electrical rack. From it the displacement and therefore stress on the model can be obtained. These calculations can be made for any loading, whether static or dynamic in nature. If a definition of the electrical or mechanical functionality of the instrumentation is required, additional information must be acquired. The failure plane (functionality as a function of excitation amplitude, duration, frequency, and type) would be useful. This information should also include the influence of operating conditions, i.e., pressure, voltage, etc., and direction of excitation on the functionality. A device may be extremely sensitive to excitation in one axis and not in another. The development of failure planes will be further discussed in Section 7.0

6.4.3 Nonlinearities

Another limitation of the model developed is that it was based on a purely linear system. Most nonlinearities associated with this type of structure are in its damping and stiffness characteristic. As the level of excitation is increased, the damping becomes greater. Therefore the damping values obtained from the log decay and impact testing may not accurately represent the damping at full level earthquake simulation. One area of nonlinearity not considered were changes in stiffness due to physical restraints. This was evident when looking at the time histories for location 5. They showed much higher peaks in the positive direction, towards the back of the electrical rack, than was evident in the forward direction. It was felt that this could be the result of two conditions: (1) the effect of UNISTRUT contact at the back of the test item, and (2) the weights were attached at their center to the rear panel of the box. Both of these would tend to result in a much greater stiffness in one direction than the other giving a nonlinearity. In an attempt to limit computational requirement the model was restricted to linear response.

6.5 Combination of Dynamic Environments

An additional series of tests were performed to study the effect of a combined dynamic environment on the electrical rack. The two environments were the earthquake with frequency content from 1.0 to 33.0 Hz and the Safety Relief Valve, SRV, environment with excitation in the 30.0 to 60.0 Hz range. A R.G. 1.60 earthquake was used for this test. The SRV excitation was obtained by multiplying a bandpass random signal by a half sine wave pulse with a duration of either two or five seconds. The amplitude of the resulting signal was adjusted such that the peak acceleration was approximately 0.5 g's. Three runs on each horizontal axis were run for each burst duration. These were: (1) earthquake only, (2) SRV only, and (3) earthquake plus SRV. The SRV event was initiated approximately fifteen seconds into the earthquake event during the strong motion portion of the signal.

Samples of the earthquake and SRV time histories are given in Figure 6.5-1 and 6.5-2 respectively. The two shown are the horizontal components of X-Z excitation and a five second SRV burst. The high frequency content of the SRV signal can be easily seen. After the signals were digitized the shock response spectrum for each signal was obtained, Figure 6.5-3. Also shown is the SRSS of the two signals. This SRSS shock response spectra was then compared to the TRS of the combined signal. It was determined that the TRS was significantly higher than the SRSS value for the frequency range where the SRV signal dominated the response. Analysis of the results indicated that this was due in part to the mechanical nature of the seismic simulator. For low level excitation, similar to the SRV testing, a large signal is required just to overcome table friction. When this is then combined with the earthquake signal, which has already overcome most of this friction, the relative level becomes higher. Therefore, it was impossible to directly compare the results.

An alternative approach was taken by adding the time histories of input and response to earthquake and SRV signals on the DEC PDP 11/70. A shock response spectrum was then calculated for these addded signals, Figure 6.5-4, and this compared well with the SRSS response spectrum. A similar approach was taken to look at the PSD of the two signals, but in this case the PSDs were added. Again the comparison, Figures 6.5-5 and 6.5-6, was favorable. The PSDs were calculated for only that portion of the signals during which the SRV was present.

The above set of analysis was performed on signals whose frequency content was widely separated. An artificial SRV signal, called shortened earthquake, with similar frequency content to the earthquake was developed. It consisted of the vertical acceleration multiplied by a time function to produce the time history shown in Figure 6.9-8. Analysis was then performed on that signal and the earthquake signal shown in Figure 6.5-7. The calculated response spectra of the individual signals and the summed signals are given in Figures 6.5-9 and 6.5-10. Once again the SRSS of the individual signals were comparable

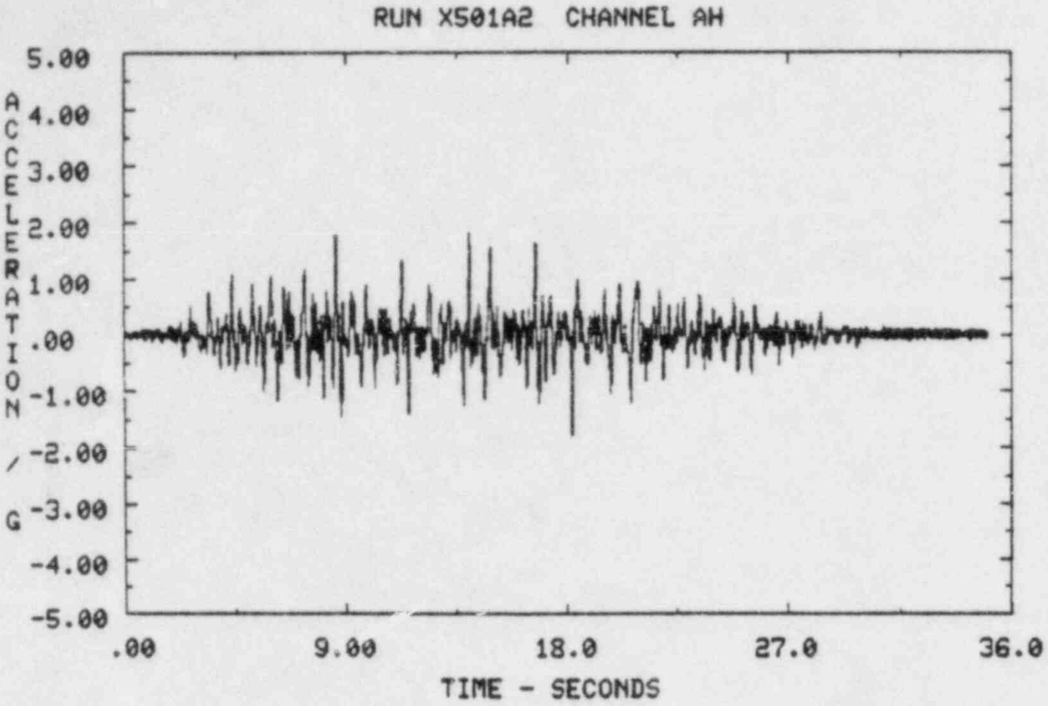


Figure 6.5-1. Earthquake Time History

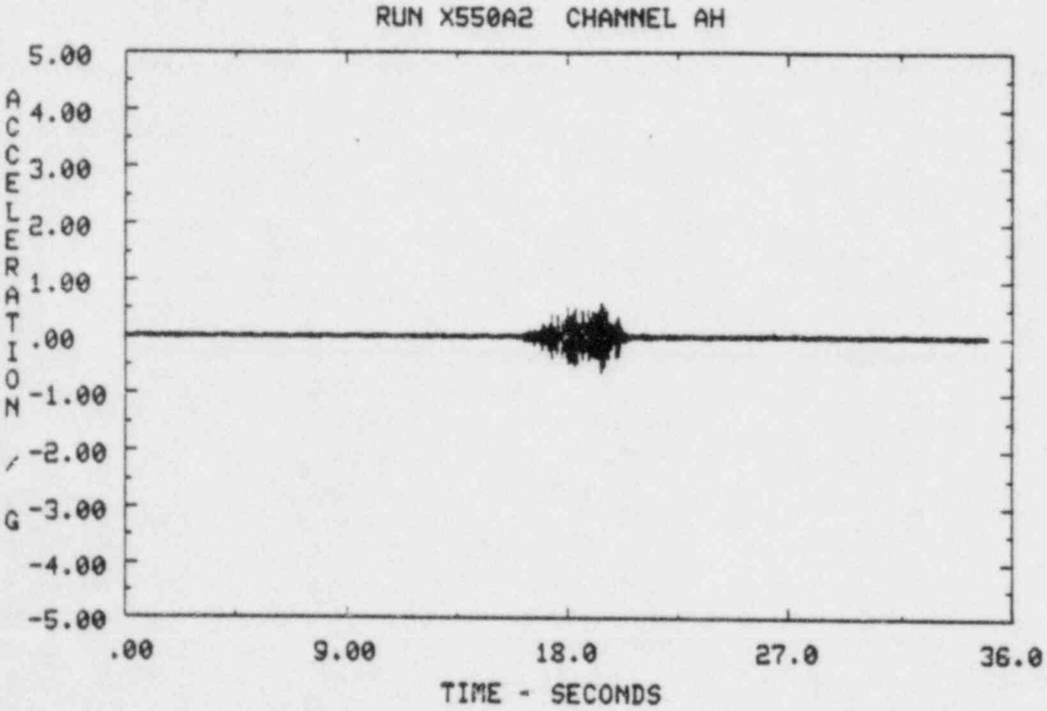


Figure 6.5-2. SRV Time History

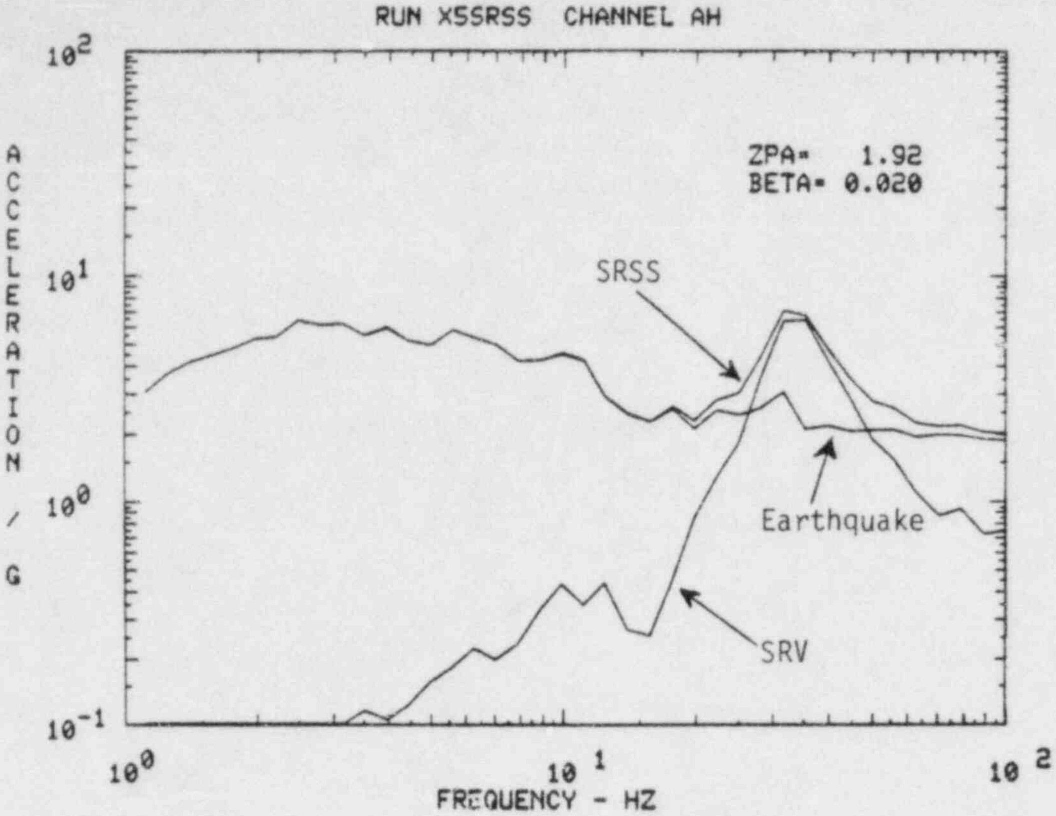


Figure 6.5-3. SRSS of Response Spectrum for Earthquake and SRV

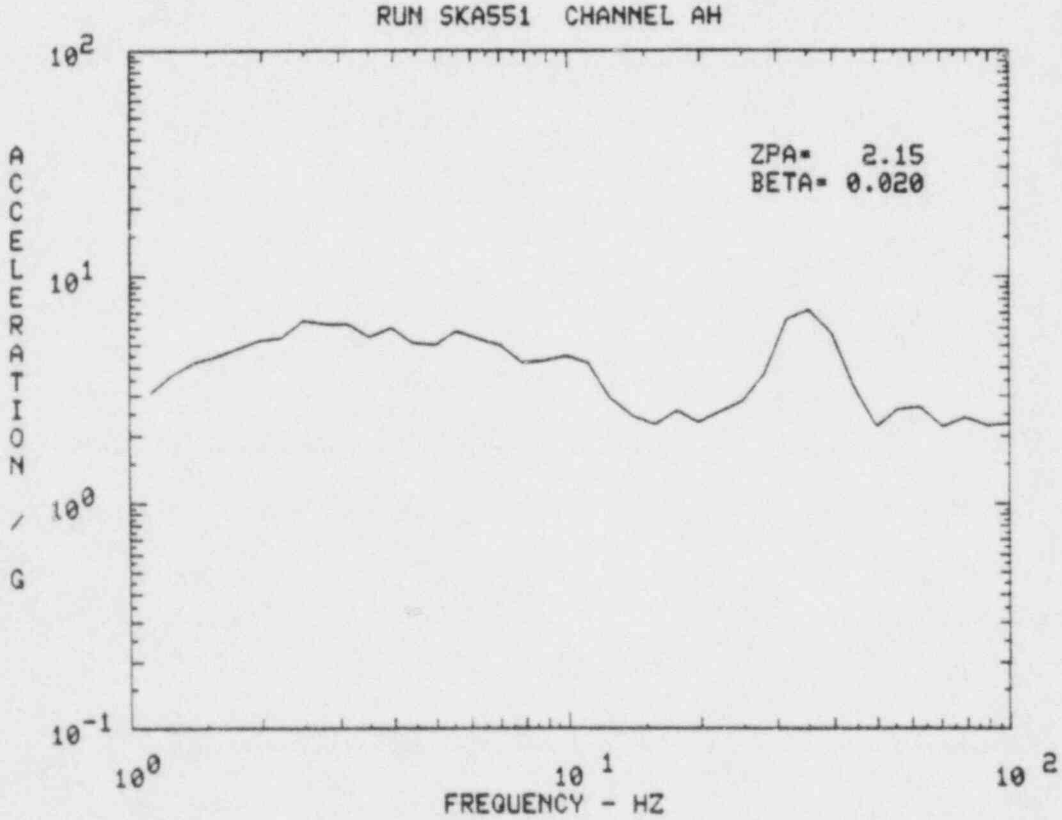


Figure 6.5-4. Response Spectrum for Earthquake and SRV

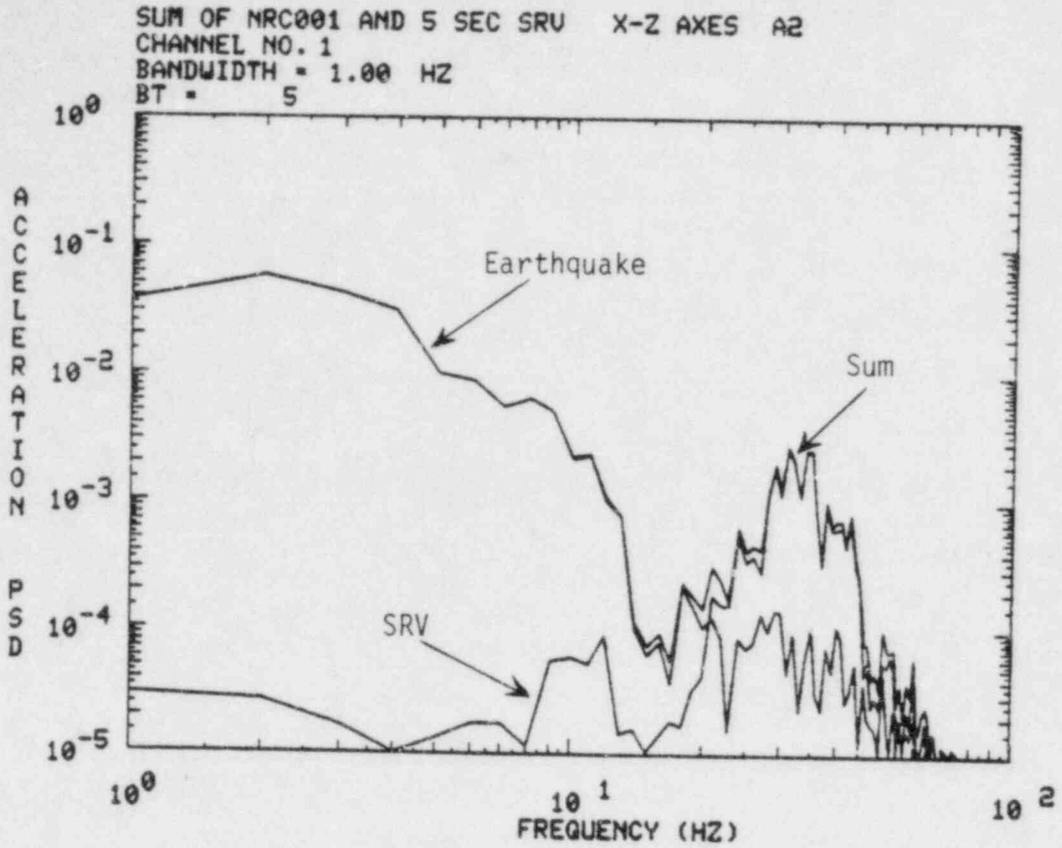


Figure 6.5-5. Sum of Power Spectra for Earthquake and SRV

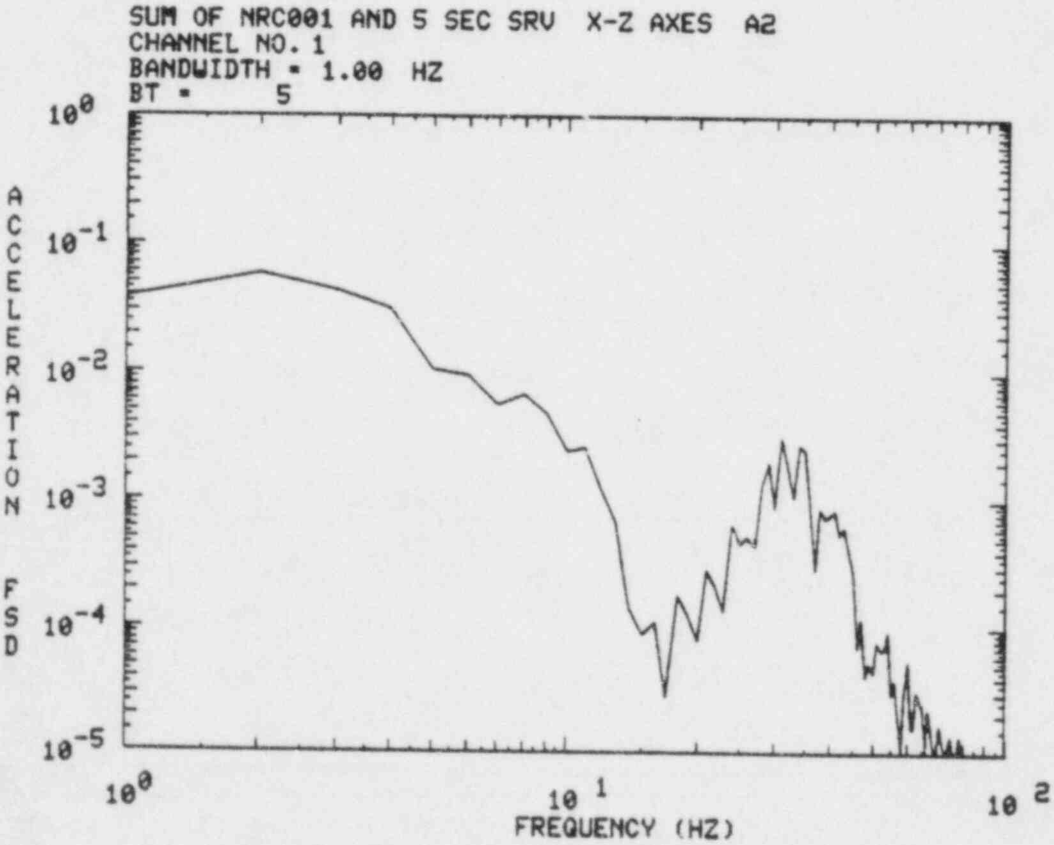


Figure 6.5-6. Power Spectrum of Combined Earthquake and SRV Time Histories

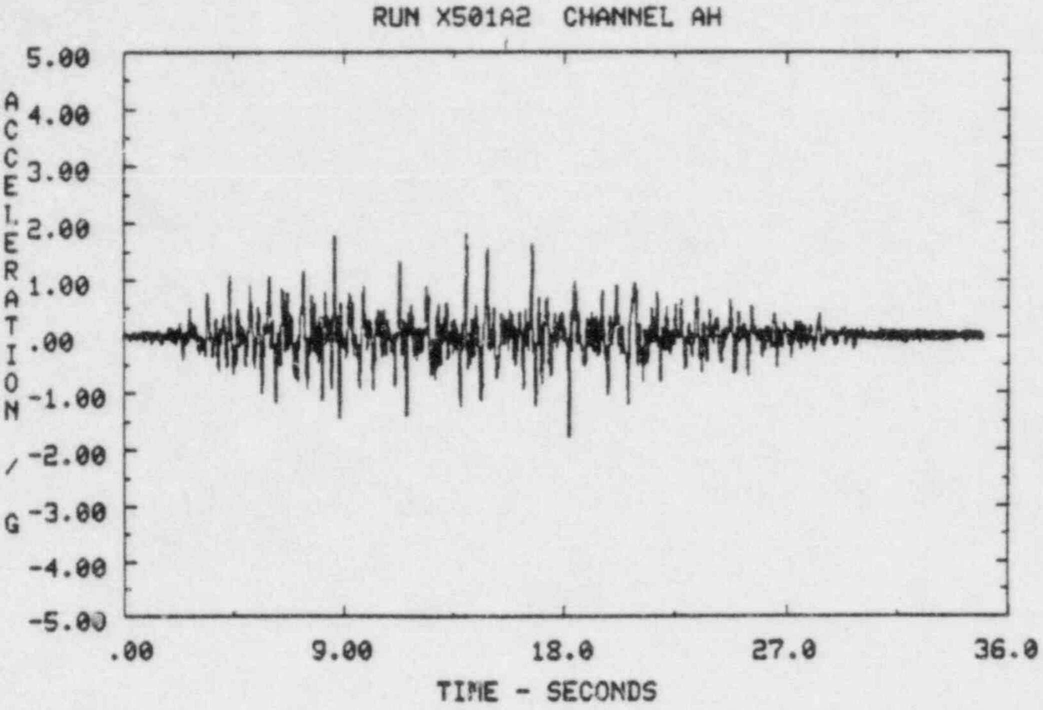


Figure 6.5-7. Earthquake Time History

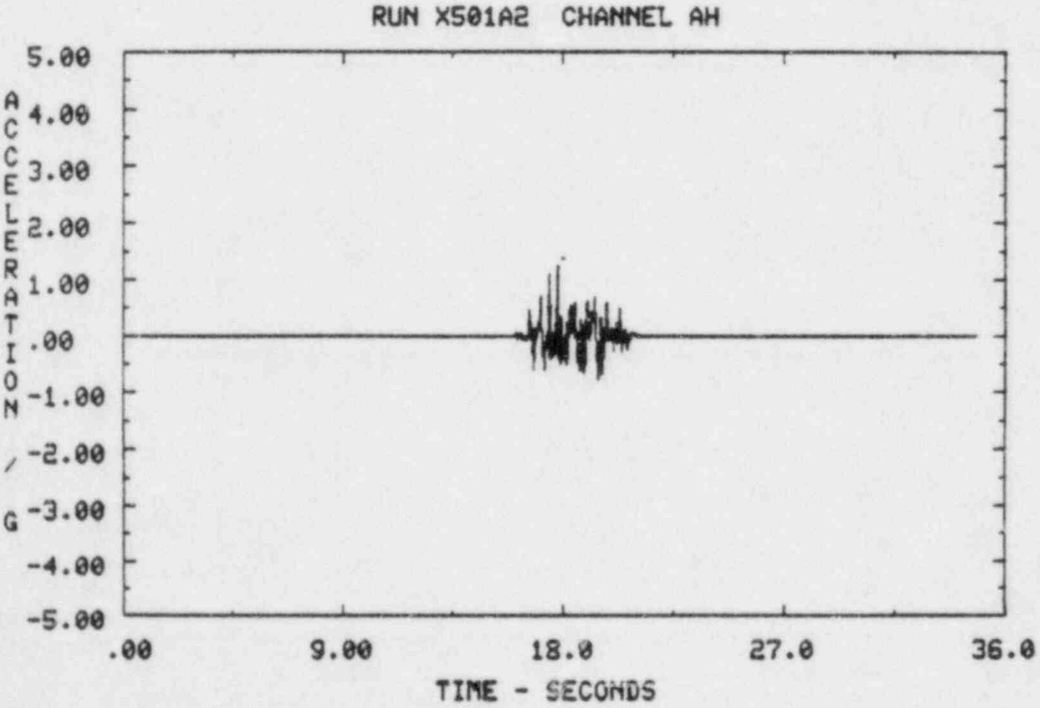


Figure 6.5-8. Shortened Earthquake Time History

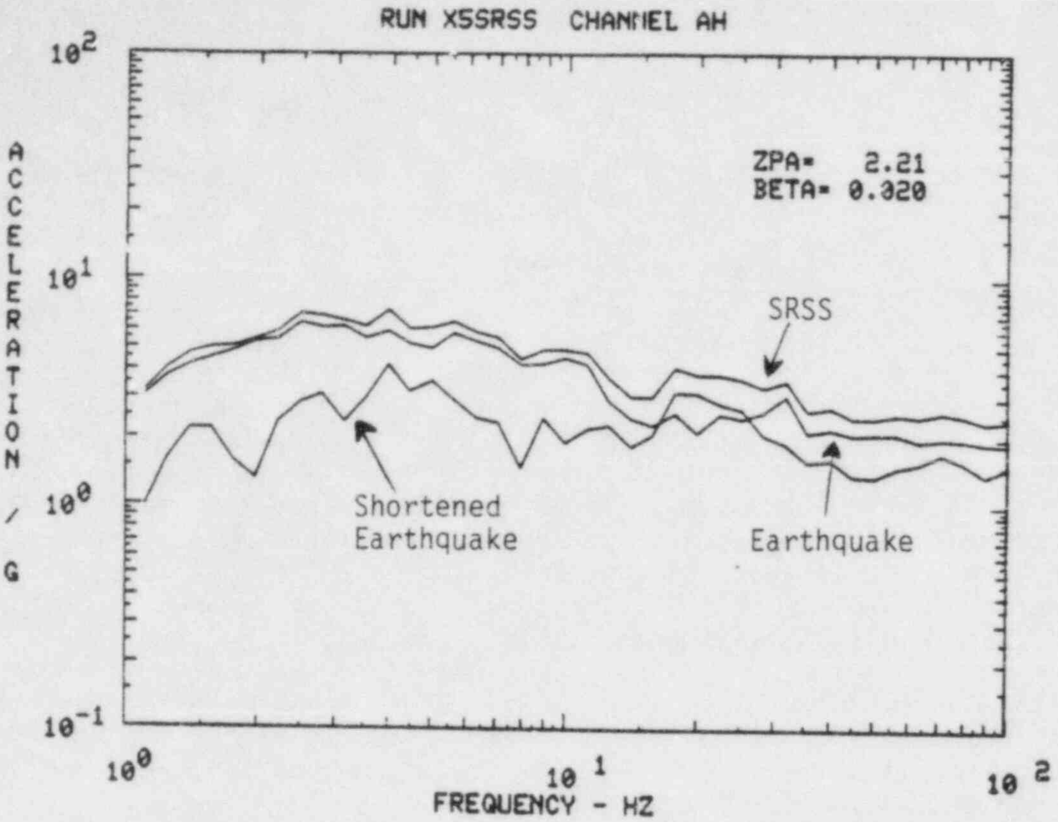


Figure 6.5-9. SRSS of Response Spectra for Individual Time Histories

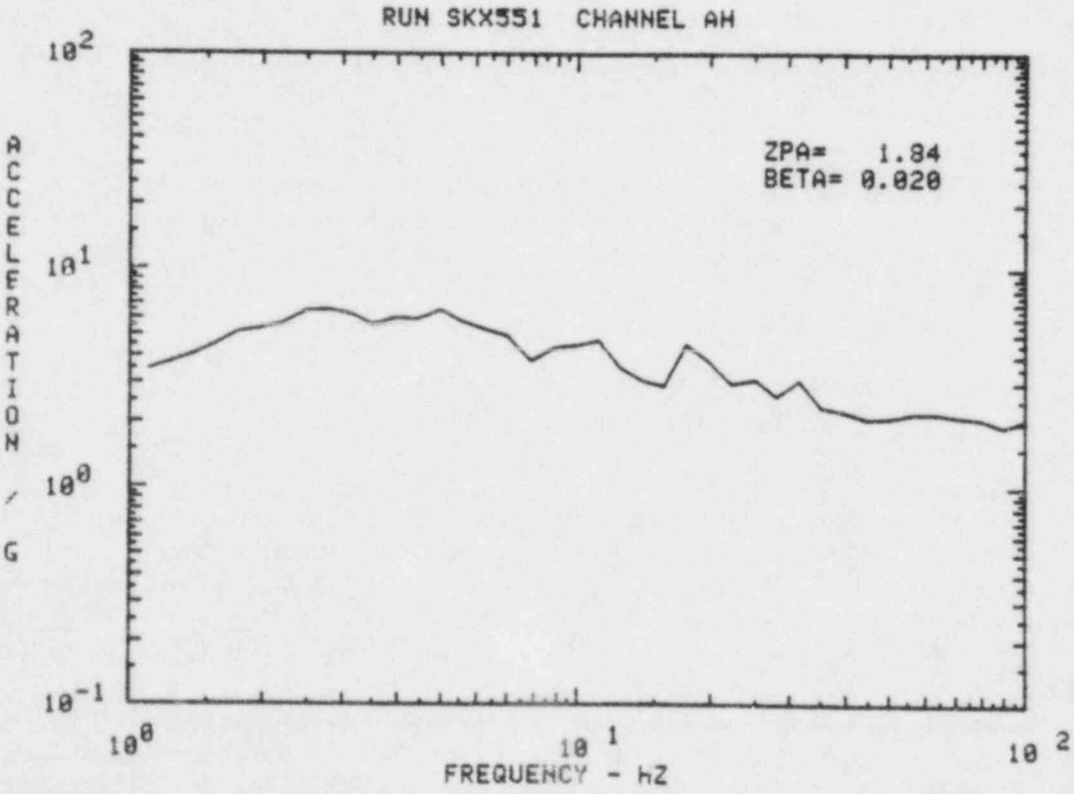


Figure 6.5-10. Response Spectrum of Combined Time Histories

to shock spectra of the summed signals. Similar results were obtained when comparing the PSD results, Figures 6.5-11 and 6.5-12.

6.6 In-Situ Modeling Procedures

Equipment located in current operating plants has been qualified by a variety of procedures most of which preceded the current criteria given in Reference [6]. Review of those procedures reveal that requalification to newer criteria may be necessary in some cases, and upgrading of equipment to higher stress levels may be appropriate in others. In either case, loss of the equipment from the plant for test purposes is very undesirable, since plant shutdowns may be required. The concept of in-situ testing, as described in Reference [1] appears to be one approach to requalification of such equipment, whereby a combined inplant test and subsequent analysis is performed.

In-situ testing in general involves the measurement of equipment dynamic properties while installed in the normal operating environment. There are three areas for which in-situ testing is typically used for nuclear plant equipment:

(1) Proof testing.
(2) Development of data for verification of independently formulated analytical models.
(3) Direct development of analytical models.

Proof testing is rarely done in this manner, and is not discussed further in this report. The use of in-situ measurements for the verification of the analytical model has already been discussed, Section 5.2. Direct development of analytical models will be discussed in this section. For this, the analytical model of the equipment is derived directly from in-situ measurements. This procedure has been used extensively in the automotive and aerospace industry. The primary difficulty associated with the application to earthquake engineering is transformation of the fixed-base in-situ measurements to the moving-base coordinates necessary for earthquake excitation. Procedures for this transformation will be discussed at length herein.

For those components whose structural integrity completely assures proper functionality, seismic requalification can be performed by analysis, with complementary in-situ test determination of equipment natural frequencies and modal properties only for analytical model verification. On the other hand, for some equipment generation of an analytical model directly from the in-situ measurements is highly desirable, so that subsequent analysis with this model can then be performed to predict appropriate responses for the structure and possible included instrumentation. It is this latter approach which is being considered verbally by various organizations, although no exact procedures have yet appeared in publication. As noted earlier, the difficulty is transformation from the fixed base in-situ measurements to the moving base earthquake environment. In view of the importance of this subject area, a complete approach to this procedure was formulated and carried out on the electrical rack. The intent was to seek potential pitfalls in the use of the method, as well as to present a

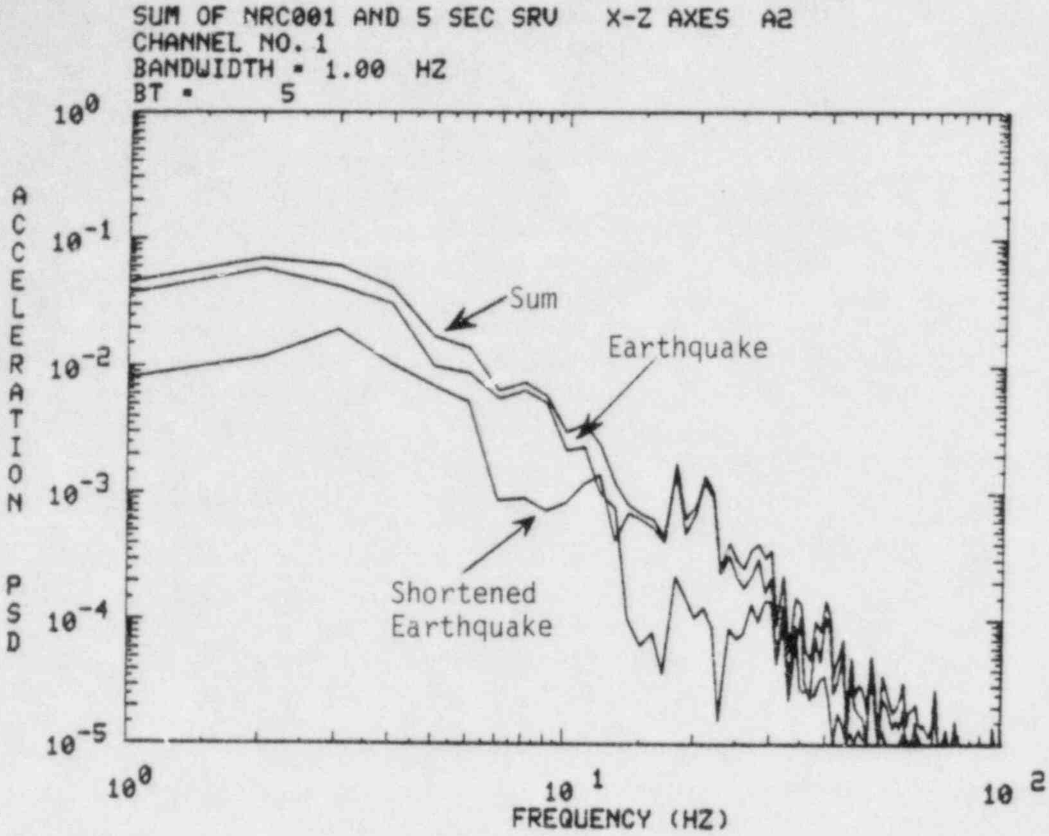


Figure 6.5-11. Sum of Power Spectra for Individual Time Histories

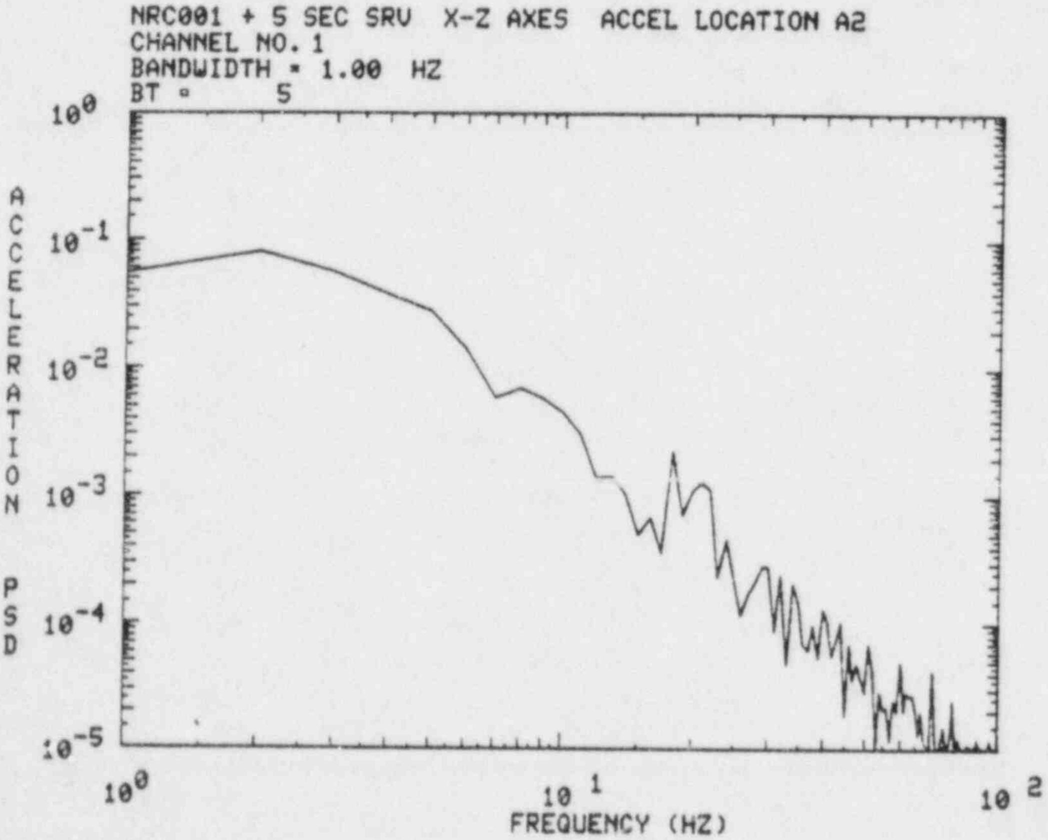


Figure 6.5-12. Power Spectrum of Combined Time Histories

documented approach in the open literature. Specifically, the procedure necessary to develop a required response spectrum for an instrument located at an elevated position on the local panel when mounted in a plant will be considered. The type and extent of in-situ measurements required, development of corresponding analytical model, and prediction of earthquake responses at an elevated instrument position will be carried out in detail. The discussion begins with the fundamental background necessary for understanding of the complete approach.

6.6.1 General Approach

6.6.1.1 Basic Equation of Motion

As a point of departure to describe the necessary in-situ measurements required to produce component elevated required response spectra, the fundamental equations of motion of a seismically excited system comprised of several components of interest which are contained in a base fixed structure will now be given. Consistent with the finite element approach for dynamic modeling of a structure with N node points (each with 3 translational and 3 rotational components) we may write the basic system equation of motion as

$$[M]\ \{\ddot{x}\} + [C]\ \{\dot{x}\} + [K]\ \{x\} = \{F\} \tag{6-1}$$

where [M], [C], and [K] are the assembled 6Nx6N mass, proportional damping, and stiffness matrices of the structure, and $\{\ddot{x}\}$, $\{\dot{x}\}$, and $\{x\}$ are the absolute nodal acceleration, velocity and displacement 6Nx1 vectors which completely describe the motion of the structure. $\{F\}$ is a 6Nx1 vector of the external nodal forces applied to the structure. Introducing 6x1 base motion vectors $\{w\}$, $\{\dot{w}\}$ and $\{\ddot{w}\}$, the 6Nx1 relative motion vector of the system $\{u\}$ with respect to the base is

$$\begin{aligned} \{u\} &= \{x\} - [T]\ \{w\} \\ \{\dot{u}\} &= \{\dot{x}\} - [T]\ \{\dot{w}\} \\ \{\ddot{u}\} &= \{\ddot{x}\} - [T]\ \{\ddot{w}\} \end{aligned} \tag{6-2}$$

and

where [T] is a 6Nx6 transformation matrix which in general relates the six component base motion vector $\{w\}^T = \lfloor X, Y, Z, \theta_x, \theta_y, \theta_z \rfloor$ to motion at each of the N structural node points.

The corresponding equations of motion for zero externally applied forces are

$$\begin{aligned} &[M]\ \{\ddot{x}\} + [C]\ (\{\dot{x}\} - [T]\ \{\dot{w}\}) \\ &+ [K]\ (\{x\} - [T]\{w\}) = \{0\} \end{aligned} \tag{6-3}$$

Here we recall that inertia forces are generated by absolute acceleration while damping and restoring forces are developed by relative motion of the structure. In terms of relative motion of the structure we may write

$$[M]\ \{\ddot{u}\} + [C]\ \{\dot{u}\} + [K]\ \{u\} = -[M]\ [T]\ \{\ddot{w}\} \tag{6-4}$$

Solution of the above equation is obtained in terms of the homogeneous system of undamped normal mode eigenvectors resulting in a system of R uncoupled second order modal equations of the form

$$m_{rr}\,\ddot{\eta}_r + 2\beta_r\omega_r m_{rr}\dot{\eta}_r + k_{rr}\,\eta_r = -[\phi]^T[M][T]\,\{\ddot{w}\} \qquad (6\text{-}5)$$

$$r = 1,2,3\ldots R$$

or

$$\ddot{\eta}_r + 2\beta_r\omega_r\dot{\eta}_r + \omega_r^2\,\eta_r = -\frac{[\phi]^T[M][T]\,\{\ddot{w}\}}{m_{rr}}\,. \qquad (6\text{-}6)$$

The 6Nx1 nodal relative displacement vector $\{u\}$, is related to the Rx1 modal displacement vector $\{\eta\}$ via the 6NxR eigenvector matrix $[\phi]$ as

$$\{u\} = [\phi]\,\{\eta\} \qquad (6\text{-}7)$$

where $[\phi] = [\{\phi_1\}, \{\phi_2\}, \ldots\{\phi_R\}]$ and $\{\eta\}^T = \lfloor \eta_1, \eta_2, \ldots\eta_R \rfloor$. The generalized mass, m_{rr}, and stiffness, k_{rr}, are defined by the orthogonality properties of the eigenvectors as

$$\left[\ulcorner m_{rr}\lrcorner\right] = [\phi]^T\,[M]\,[\phi]$$

and

$$\left[\ulcorner k_{rr}\lrcorner\right] = [\phi]^T\,[K]\cdot[\phi] = \left[\ulcorner\omega_r^2\lrcorner\right]\left[\ulcorner m_{rr}\lrcorner\right]\,. \qquad (6\text{-}8)$$

The modal equations of motion, as given in Equation (6-6), can be rewritten as

$$\ddot{\eta}_r + 2\beta_r\omega_r\dot{\eta} + \omega_r^2\eta = -\,\{\gamma_r\}^T\,\{\ddot{w}\} \qquad (6\text{-}9)$$

where the modal participation vector is defined by

$$\{\gamma_r\}^T = \frac{\{\phi_r\}^T[M][T]}{m_{rr}} \qquad (6\text{-}10)$$

In general, the modal participation vector consists of six modal participation factors, one corresponding to each of the six possible components of base motion $\{\ddot{w}\}$.

For a specified component of the base motion input time history $w_i(t)$ the corresponding modal time histories $\eta_r(t)$ may be calculated from a direct time history integration of Equation (6-9). The relative motion of the structure would then be computed via the relationship given in Equation (6-7) and the absolute motions computed via Equation (6-2). Once the nodal time histories are known, a shock spectrum analysis of each nodal response would then yield the desired component elevated required response spectrum. The time history integration process is straightforward, however, computationally very intense.

A much more computationally efficient method of developing an elevated response spectrum is to work with the equivalent power spectrum. The transformation between the power spectrum (PS) and response spectrum (RS) and the reverse transformation was discussed previously in Section 2.0 of this report. To make use of the power spectrum approach we need to develop the transfer functions relating elevated responses to base excitations. Assuming that the base input motions are uncorrelated then the power spectrum response $G_i^k(\omega)$, at elevated point i in direction k is simply

$$G_i^k(\omega) = \sum_{j=1}^{6} \left| H_{ij}^k(\omega) \right|^2 G_j(\omega) \tag{6-11}$$

where H_{ij}^k is the base to elevated motion transfer function due to motion in the j^{th} direction and $G_j(\omega)$ is the base input power spectrum in the j^{th} direction. The base input power spectra are obtained directly from the base input response spectra via the methods discussed in Section 2.0.

Assuming that we are working with acceleration responses we can obtain the r^{th} modal acceleration directly from Equation (6-9) as

$$\ddot{\eta}_r = \frac{\omega^2 \{\gamma_r\}^T \{\ddot{w}\}}{[(\omega_r^2 - \omega^2) + i\ 2\beta_r \omega_r \omega\ ]} \tag{6-12}$$

The r^{th} modal transfer function corresponding to the j^{th} base input direction is then simply

$$h_{rj} = (\ddot{\eta}_r / \ddot{w}_j) = \frac{\omega^2\ \{\gamma_r\}^T \{\delta_j\}}{[(\omega_r^2 - \omega^2) + i\ 2\beta_r \omega_r \omega]} \tag{6-13}$$

where $\{\delta_j\}$ is a vector selecting the j^{th} input direction, i.e., for Y input motion $\{\delta_j\}^T = \lfloor 0, 1, 0, 0, 0 \rfloor$, etc. From Equation (6-7) the relative acceleration response function for motion at the i^{th} node in the k^{th} direction is written as

$$\bar{H}_{ij}^k = \sum_{r=1}^{R} \phi_{ir}^k h_{rj} . \tag{6-14}$$

The absolute acceleration response transfer function is determined from Equation (6-2) as

$$H_{ij}^k = \sum_{r=1}^{R} \phi_{ir}^k\ h_{rj} + \delta_{kj} \tag{6-15}$$

where $\delta_{kj} = 0$ for $k \neq j$ and $\delta_{kj} = 1$ for $k = j$. Thus the acceleration due to base input motion is added directly to the relative motion if the response is in the direction of excitation.

6.6.1.2 In Situ Measurements

The expressions given in Equations (6-11) and (6-15) allow complete predictions of elevated power spectra at response point i and direction k due to specified uncorrelated power spectra in each base input direction. The relative motion modal transfer functions h_{rj} as defined in Equation (6-13) and the mode shape vectors $\{\phi_r\}$ for each normal mode may be computed via parameters obtained from in situ measurements on the structure in the base fixed plant installed configuration. Modern modal analysis packages based on microprocessor based Fast Fourier Transform (FFT) analyzers are capable of characterizing a structure by detecting its normal modes of vibration and certain modal properties, i.e., mass, stiffness, damping, mode shape, and frequency characteristics. The open literature available on modal analysis test techniques is quite extensive. A concise literature review in this area is given by Luk [19]. The primary physical properties extracted from the modal analysis operation are the structure normal mode frequencies ω_r, mode shapes $\{\phi_r\}$ and the critical damping ratios, β_r for a fixed base condition. While several systems can compute the modal mass, m_{rr}, it has been the author's experience that m_{rr} cannot be determined accurately due to influence of closely spaced modes.

In order to compute the desired transfer functions the modal participation factors of the system must be found. From Equation (6-10) we can see this would require knowing the physical mass matrix of the structure, [M], and the modal masses, m_{rr}. The physical mass and modal mass are related through the orthogonality of the system eigenvectors, i.e., mode shapes $\{\phi_r\}$ as given by Equation (6-8). However, in order to extract both the physical mass, [M], and modal mass, m_{rr}, from that expression several assumptions are required. First, it is assumed that from the in situ measurements the system mode shapes, $\{\phi_r\}$, are accurately determined. That is, sufficient measurements have been made to describe the nodes and anti-nodes of the mode shapes. The importance of this assumption will be demonstrated with several example calculations in a following section. The physical mass matrix is assumed to be diagonal, i.e., uncoupled. Two conditions on the physical masses are present in the modal mass matrix definition:

Condition 1. Definition of the modal masses themselves

$$m_{rr} = \{\phi_r\}^T [M] \{\phi_r\} \qquad r = 1,2,\ldots R \tag{6-16}$$

and most important

Condition 2. Mass-orthogonality of the eigenvectors,

$$\{\phi_j\}^T [M] \{\phi_i\} = 0 \qquad i, j = 1,2\ldots R \text{ for } i \neq j \tag{6-17}$$

The indicated modal mass determination is highly subject to experimental error associated with the procedures used in modal extraction techniques, such as circle or line fitting with closely spaced modes. Errors in modal mass extraction can lead to a set of conflicting requirements on the eigenvectors between the two stated conditions. Initial numerical experimentation revealed that extremely accurate modal masses must be used in Condition #1 to extract the physical mass matrix and simultaneously satisfy Condition #2. Recall that only the relative distribution of physical mass is important in the computation of the modal participation factors, this is seen by writing

$$\{\gamma_r\}^T = \{\phi_r\}^T [M][T] / \{\phi_r\}^T [M] \{\phi_r\} \tag{6-17}$$

and therefore the modal masses need not be known. As a result, Condition #1 was removed from further consideration. However, we may note that Condition #2, the mass orthogonality of the eigenvectors, specifies the physical mass distribution to within an undetermined constant and the constant is arbitrary with respect to the modal participation factors. To uniquely determine the physical mass distribution an auxiliary condition on the physical mass is used with Condition #2. Several possibilities for the auxiliary condition are appropriate, such as making one of the modal masses equal to unity or the sum of physical masses equal to a constant (1, or the estimated total physical mass of structure M_o).

6.6.1.3 Determination of the Nodal Mass Distribution

The physical diagonal mass matrix elements are thus determined from the auxiliary condition:

$$\sum_{i=1}^{N} \phi_{i1}\, m_i\, \phi_{i1} = 1 = \tilde{m}_{11} \tag{6-18a}$$

or

$$\sum_{i=1}^{N} m_i = M_o \tag{6-18b}$$

and eigenvector mass orthogonality condition

$$\sum_{i=1}^{N} \Phi_{ik}\, m_i = 0 \quad k = 1,2,\ldots.K, \tag{6-19}$$

where $K = R\,(R-1)/2$ from use of off diagonal elements only, and where $\Phi_{ik} = \phi_{pi}\,\phi_{qi}$, m_i are the physical mass diagonal elements, and p and q are mode numbers which participate in the orthogonality condition such that $p = q = 1,2,3,\ldots R$ with $q > p$. The number of equations K+1 that result from the process will generally not equal the number of unknowns N, which are the physical masses at the N measurement locations. The two solution strategies which were developed to solve for the physical mass distribution will now be briefly described.

6.6.1.3.1 Optimization Approach - MASOPT

An optimization approach was developed in terms of an objective function of the form

$$F(m_i) = (\tilde{m}_{11} - 1)^2 + \sum_{p=1}^{R} \sum_{q=p+1}^{R} (\tilde{m}_{pq})^2 \qquad (6\text{-}20)$$

where $\tilde{m}_{11}$ is the computed first eigenvector modal mass and $\tilde{m}_{pq}$ are the computed off diagonal modal mass terms which occur due to an initial guess of the physical mass elements m_i, $i = 1,2,3,\ldots N$. We seek a distribution of masses m_i that will drive the objective function $F(m_i)$ to zero. The procedure used was based on the gradient projection method first developed by J. B. Rosen [20]. The algorithm proceeds as follows:

(1) A feasible starting point m_i's and step size S are selected; $m_i = 0$, $i = 1,2,\ldots N$ and $S = 0.1$.

(2) The derivatives of the objective with respect to the independent variables $\partial F/\partial m_i$, $i = 1,2,3,\ldots N$ are evaluated at the base point and the normalized direction vector components, V_i, are determined:

$$V_i = \frac{\pm \frac{\partial F}{\partial m_i}}{\sqrt{\sum_{j=1}^{N} \left(\frac{\partial F}{\partial m_j}\right)^2}} \qquad (6\text{-}21)$$

if $\partial F/\partial m_i$ are less than a presecribed limit for all $i = 1,2,3,\ldots N$, then the procedure is stopped since no improvement in the base point would be reached by continuing, if not:

(3) A new point is then located as follows:

$$\text{new } m_i = \text{old } m_i + S\, V_i \quad i = 1,2,\cdots N \qquad (6\text{-}22)$$

subject to the constraint that the new m_i must be equal to or greater than zero.

(4) The objective function is evaluated and the following possibilities are then considered.

   (a) If an improvement in the objective function occurs, the step size is doubled and the process repeated.

   (b) If the function is not improved at the new point, the step size is halved for the next move from the last successful point.

For the case where the number of system knowns, k+1, are greater than or equal to the number of unknown nodal masses N the procedure yields a unique solution. However, when N > K+1 the solution is not unique and very sensitive to the starting point of the procedure. It has been determined that the best starting point is $m_i = 0$ allowing the procedure to converge to a physical mass representation wherein masses of nodes with little motion remain at zero, weighting the anti-node masses heavily in the procedure. For this case the resulting mass distribution is quite sensitive to the accuracy of the measured mode shape. To improve this condition a second method was developed.

6.6.1.3.2 Mass Smoothing Approach- UMASS

In the mass smoothing approach a set of N weighted equations are added to the principle K+1 equations to insure an overdetermined set of equations. The N smoothing equations describe the condition that the variance of the physical mass distribution is a minimum:

That is the variance,

$$\sigma^2(m_i) = \sum_{i=1}^{N} \left(m_i - \frac{1}{N} \sum_{j=1}^{N} m_j \right)^2 \qquad (6\text{-}23)$$

is to be a minimum, thereby forcing

$$\frac{\partial \sigma^2}{\partial m_k} = 0 \qquad k = 1,2,3 \cdots N \qquad (6\text{-}24)$$

resulting in set of equations of the form

$$\left(m_k - \frac{1}{N} \sum_{j=1}^{N} m_j \right) = 0 \qquad k = 1,2,3 \ldots N \qquad (6\text{-}25)$$

which are added to Equations (6-18b) and (6-19) after multiplication by a weighting factor γ. The complete system of equations in matrix form is

$$\begin{bmatrix} 1 & 1 & 1 & \cdots & 1 \\ \phi_{11} & \phi_{12} & \phi_{13} & \cdots & \phi_{1N} \\ \phi_{21} & \phi_{22} & \phi_{21} & \cdots & \phi_{2N} \\ \phi_{31} & \phi_{32} & \phi_{33} & \cdots & \phi_{3N} \\ \vdots & & & & \\ \phi_{N1} & \phi_{N2} & \phi_{N3} & \cdots & \phi_{NN} \\ \gamma(1-\frac{1}{N}) & -\frac{\gamma}{N} & -\frac{\gamma}{N} & \cdots & -\frac{\gamma}{N} \\ -\frac{\gamma}{N} & \gamma(1-\frac{1}{N}) & -\frac{\gamma}{N} & \cdots & -\frac{\gamma}{N} \\ \vdots & & \vdots & & \\ -\frac{\gamma}{N} & -\frac{\gamma}{N} & -\frac{\gamma}{N} & \cdots & \gamma(1-\frac{1}{N}) \end{bmatrix} \begin{Bmatrix} m_i \end{Bmatrix} = \begin{Bmatrix} M_o \\ 0 \\ 0 \\ 0 \\ \vdots \\ 0 \\ 0 \\ 0 \\ \vdots \\ 0 \end{Bmatrix} \qquad (6\text{-}26)$$

The 1+ K+ N by N overdetermined system of equations is solved in a least squared sense. The weighting factor takes on values in the range from 0.1 to 0.01 depending on the conditions of the original system of equations:

(1) For the case of an undetermined system of original equations, that is a large number of unknown nodal masses are to be described by a small number of normal mode eigenvectors ($N > K+1$):

(a) A value of weighting factor γ on the order 0.1 is used to enforce a degree of uniformity in the nodal mass distribution via the smoothing equations. This is necessary to avoid singularities of the original underdetermined system.

(b) The errors developed in the eigenvector mass orthogonality terms, i.e., Equation (6-19), are computed as in Equation (6-20):

$$E\,(m_i) = \sum_{p=1}^{R} \sum_{q=p+1}^{R} (\tilde{m}_{pq})^2 \qquad (6\text{-}27)$$

where $E(m_i)$ is a measure of the error. The weighting factor γ is then incremented to minimize the error function. In general, larger values of γ are needed for systems where N is much larger than K+1.

(2) For the case of an overdetermined system of original equations, that is a small number of unknown masses is described by a larger number of eigenvalues ($N < K+1$):

(a) A small value of γ, on the order of 0.01 is used to provide artifical "numerical damping" in the system solution. High order modes for which the eigenvectors cannot be accurately obtained can result in physically unrealizable negative nodal masses which are eliminated by introducing a small value of γ.

6.6.2 Conflicting Parameter Specifications

In modal testing the trend is to select a high number of structural node points, N, at which measurements are to be taken in order to accurately define the normal mode eigenvectors, i.e., mode shapes, $[\phi_r]$. The number of degrees of freedom (DOF) to accurately describe a mode shape is highly dependent on system geometry, however for a simple cantilever beam it is not unreasonable to choose four to five points between nodes of the mode. This being the case, the number of DOF, which for a 1-D system equals the number of nodes required to accurately define the r^{th} mode would be on the order of three to five times the total number of modes. If such measurements were taken, it can be seen by the data given in Figure 6.6-1 that the system measurements would result in an under-determined system for the solution of the nodal mass distribution if less than 11 normal modes were recorded. With the emphasis in the seismic area to design structures with a first normal mode resonance beyond 33 Hz, the number of modes within the frequency range of interest could be very few. Thus one can see a conflict in measurement specifiction if an over-determined or under-determined system of equations are desired for the specification of the nodal masses, i.e., the modal participation factors.

6.6.3 Analysis of Method

The importance of developing the UMASS algorithm for solution of under-determined systems, i.e., for $N > K+1$, is seen by the conflicting parameter specification described above. In this section we will present several example calculations using both MASOPT and UMASS to demonstrate the level of accuracy that can be obtained in modal participation factor calculations, from both measured and analytically determined mode shapes.

A uniform cross-section (0.125 in. x 1.0 in.) aluminum beam 14 in. in length was analyzed both analytically using a finite element structural modeling technique and experimentally by hammer impact testing using a modal analysis single mode circle fit technique to determine the mode shapes. Modal participation factors (MPF) were determined analytically for the first three normal modes of the structure and from the measured mode shapes via the MASOPT and UMASS routines. A comparison of results are given in Table 6-2. The experimental mode shapes were determined from measurements taken at 15 evenly spaced nodes along the length of the beam. As can be seen from the curve given in Figure 6.6-1, the $N = 15$ and $R = 3$ system falls in the under-determined system classification. The improved results computed by UMASS over those of MASOPT for this under-determined system is clearly shown by the MPF given in Table 6-2. This analysis of the simple beam can be considered verification of the analysis procedure.

Mode shape data from the finite element model of the electrical equipment rack previously discussed in Section 5.0 was used

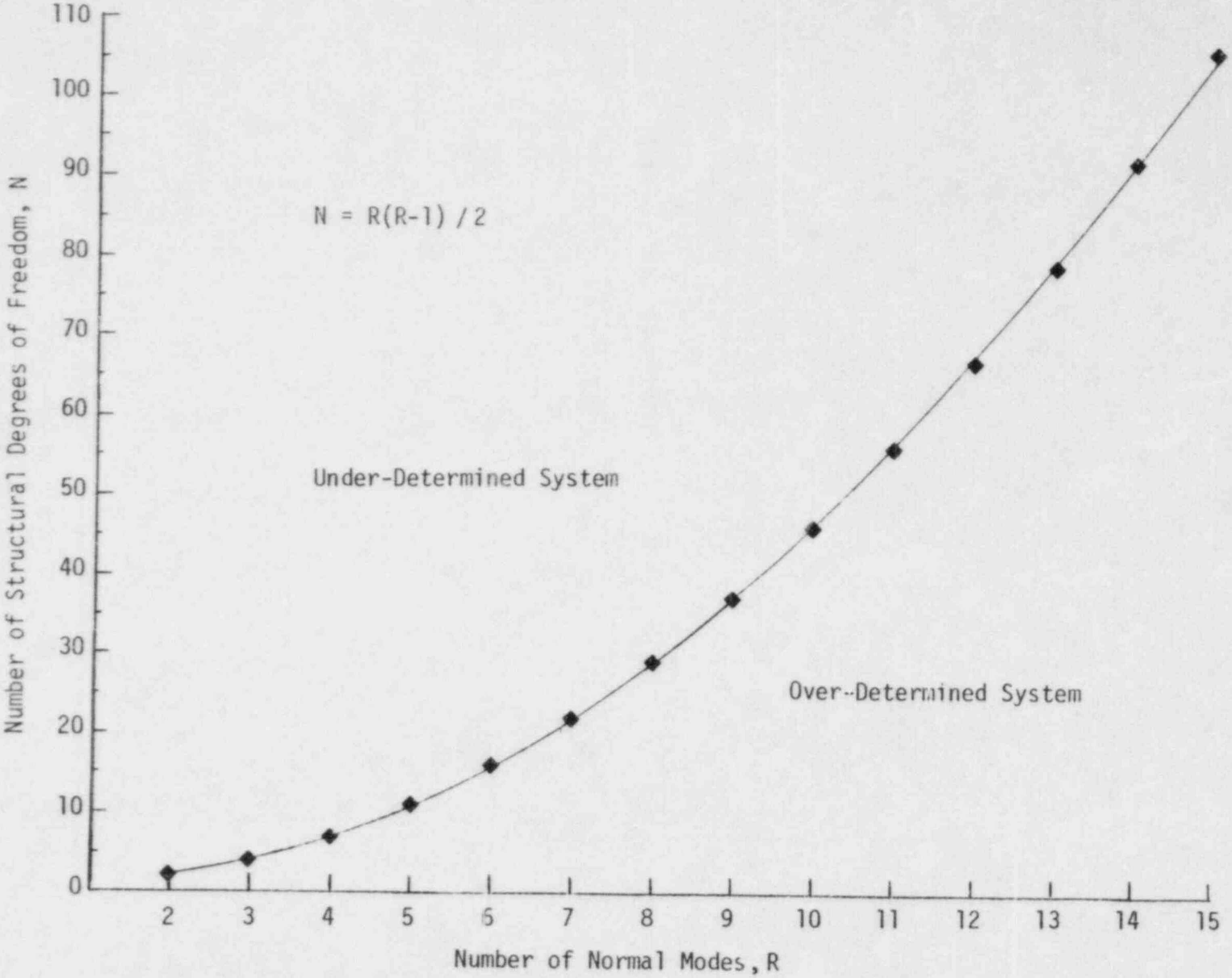


Figure 6.6-1. Relationship Between Structural Degrees of Freedom and Normal Modes for a Well-Defined System

TABLE 6-2 CANTILEVER BEAM FREQUENCIES AND MODAL PARTICIPATION FACTORS

Mode No. R	Frequency - Hz		Modal Participation Factors		
	Analytical	Measured	Analytical	MASOPT	UMASS
1	20.28	20.0	-1.595	-1.484	-1.530
2	126.35	123.75	-0.796	-0.608	-0.724
3	351.96	347.5	0.513	0.256	0.411

* N = 15, evenly spaced nodes.

TABLE 6-3 EQUIPMENT RACK EXPERIMENTAL SIMULATION, MODAL PARTICIPATION FACTORS

Mode No. R	D.O.F.*	Frequency Hz	Modal Participation Factors				
			Analytical	MASOPT		UMASS	
				R = 6	R = 7	R = 6	R = 7
1	1	14.6	0.0019	0.0012	0.0024	0.0019	0.0031
	2		1.3009	1.2730	1.2060	1.296	1.194
2	1	24.4	2.3318	2.0140	1.8550	2.071	1.961
	2		-0.0306	-0.0207	-0.0196	-0.0249	-0.0225
3	1	40.5	-0.5601	-0.5328	-0.3593	-0.5088	-0.1939
	2		-0.1729	-0.1831	0.0010	-0.1604	-0.0392
4	1	42.8	-1.1189	-1.0170	-0.8827	-1.0510	-1.1790
	2		0.1325	0.1122	0.0140	0.1079	0.0348
5	1	50.4	0.0220	0.0074	0.1053	0.0491	0.8786
	2		1.3249	0.3663	-0.0482	0.4096	-0.3672
6	1	52.4	1.1834	0.0185	-8.062	0.5407	-1.6800
	2		-0.0806	-0.0956	0.2497	0.0856	0.0988
7	1	59.9	0.5030		0.2301		-0.3798
	2		-0.7700		-0.2763		-0.8021

*Degree of Freedom at the measurement nodes.

1 - parallel to the horizontal excitation

2 - parallel and perpendicular to the horizontal excitation

to further define expected accuracies in the computation of MPF from mode shape data. Motion at 50 of the 265 node points were extracted from the computed mode shapes for the equipment rack. The 50 node points were chosen as typical of the points which would be selected for extracting mode shape data experimentally. The mode shape data were then used in MASOPT and UMASS to compute MPF for comparison to the analytical values. The results of the study are given in Table 6-3. For the seven modes considered ($R = 7$) the 50 node model represents a highly under-determined system of equations. When using six ($R = 6$) of the simulated measured mode shapes, the MASOPT and UMASS routines yield similar results with reasonably accurate predictions of the MFP of the first four ($R = 4$) modes; thereafter the mode shapes appear to be poorly defined yielding poor calculated MPF. When an additional mode is added into the calculation ($R = 7$), the additional poorly defined mode shape produces degraded results throughout all modes. This example points out the importance of accurate mode shape measurements and a potential approach of developing a scheme by which the goodness of mode shape data may be assessed based on the MPF calculations.

The data in Table 6-3 show that by including an additional ill defined mode shape the computed MPF change drastically. Thus if one were to start with a low number of modes and increment the number while monitoring the consequence of the calculated MPF, it may be possible to detect poorly defined mode shapes and eliminate their influence in the MPF calculations. Further study in this area is needed to develop the required algorithms to implement a mode selection criteria.

6.6.4 Application to Electrical Rack

The electrical equipment rack described in Section 5.0 was investigated experimentally using hammer impact modal analysis test procedures for the floor mounted condition. The mode shape data were obtained by peak picking the imaginary part of the measured nodal transfer functions and the data were used to predict corresponding modal participation factors. Results of the computations are given in Table 6-4. Comparison of MASOPT and UMASS results indicate potentially poor mode shape definition beyond $R = 4$ since at this point the two routines begin to yield noticeably different results.

To further demonstrate the use of the method an elevated response spectrum was computed for a typical earthquake excitation. The base test response spectrum for Run 001, as given in Figure 6.2-3, was first transformed to a power spectrum $G_j(\omega)$, which has already been shown as the dashed line in Figure 6.2-4. The transfer functions $H_{ij}^k(\omega)$ were then obtained from the in-situ measured eigenvectors ϕ_{ir} and the h_{rj} factors determined from Equation (6-13), and substituted into Equation (6-14). Next, Equation (6-11) was used to calculate the elevated power spectrum $G_i^k(\omega)$, which was finally transformed to an elevated response spectrum, via the method outlined in Section 2.0.

Results of the above application are given in Figure 6.6-2 for Y-Z excitation and in Figure 6.6-3 for X-Z excitation. The response is presented in terms of the elevated response spectrum at location 05 for the Run 001 excitation. Note that the analytical model did not

TABLE 6-4 EQUIPMENT RACK EXPERIMENTAL FREQUENCIES AND MODAL PARTICIPATION FACTORS

Mode No. R	D.O.F.*	Frequency Hz	Model Participation Factors	
			MASOPT	UMASS
1	1	11.6	0.125	0.134
	2		1.617	1.865
2	1	23.4	1.754	1.830
	2		-0.147	-0.150
3	1	30.9	-0.093	-0.086
	2		-0.032	-0.015
4	1	44.7	-0.203	-0.128
	2		0.238	0.225
5	1	50.0	0.171	0.187
	2		-0.036	-0.202
6	1	54.1	0.187	0.093
	2		0.148	0.236
7	1	59.4	0.632	0.995
	2		-0.005	0.038

* Degree of Freedom at the measurement nodes.

1 - parallel to the horizontal excitation

2 - parallel and perpendicular to the horizontal excitation

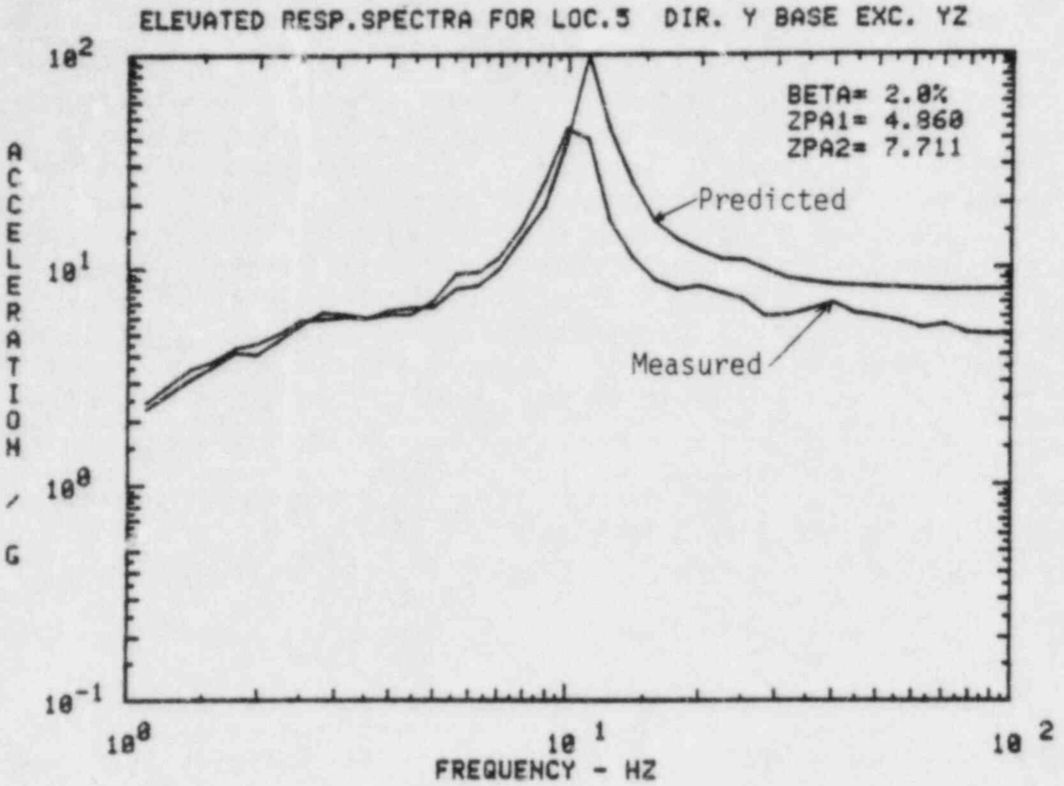


Figure 6.6-2. Measured and Predicted Response Spectra at Position 5 for Run 001 With Y-Z Excitation

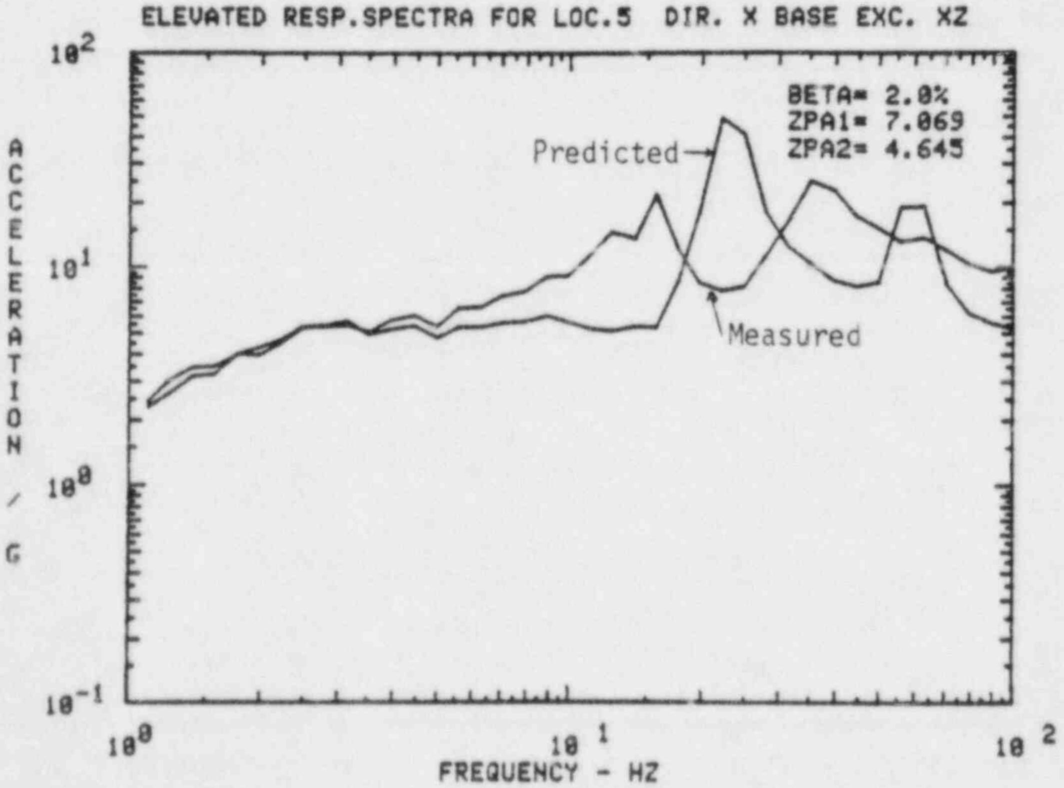


Figure 6.6-3 Measured and Predicted Response Spectra at Position 5 for Run 001 With X-Z Excitation

include any vertical motion that may have resulted in additional horizontal response. A response spectrum calculated from the measured time history is also given for comparison. In the case of Y-Z excitation the general agreement is good, although the predicted response is significantly higher (conservative) in much of the frequency range. One cause of the difference is the use of the fixed base analytical results which have been shown to be different from the table mounted condition. The results for the X-Z direction are very poor. However, this result is not surprising in view of the difference in transfer functions obtained for the first bending mode in this direction for the floor mounted specimen and the free table mounted specimen. Had the transfer functions, as used in the in-situ approach, been obtained on the specimen while mounted on the free table, we sincerely believe that a good comparison would have occurred for both of the above cases. This result further points to the sensitivity to boundary conditions of all types of qualification methods.

6.7 Multiple Axis Excitation

6.7.1 Definition of Problem

The matter of cross axis coupling, as caused by coupled response in a building, has already been approached in Section 3.2. However, another facet of the same problem can occur if principal orthogonal response axes in a structure are oriented at angles to orthogonal excitation axes. Although the principal bending axes of rectangular structures (such as cabinets, panels, etc.) may appear obvious, they still can experience coupled responses at certain frequencies, and for that matter may not be oriented parallel to the principal axes of a building in which they are housed. For that matter, even if an independent triaxial excitation of the equipment is considered for a floor level excitation simulation, true fidelity of the excitation may not be accomplished in frequency ranges where cross coupling of the building causes statistical dependence to exist between the two horizontal motions.

It is pertinent to consider what kind of structures or devices (if any) are not being tested conservatively by present biaxial testing procedures, if compared to a triaxial test procedure. It is recognized that biaxial procedures require test runs along both the XZ and YZ directions separately, while triaxial tests would allow only one run for XYZ simultaneously. In order to shed some light on this problem, the electrical rack was analyzed for the two different types of excitation.

6.7.2 Cross Axis Coupling in the Electrical Rack

The in-situ model for the electrical rack described in Section 6.6.4 was used to provide an analytical prediction of rack responses to independent biaxial and independent triaxial excitation. Although the model represents an electrical rack, similar results would be expected to occur in a building, or other comparable equipment structures. Excitation for the analytical model is taken to be represented by the test response spectrum for the respective axis with

Run 001. The excitation response spectra were transformed to PSD's and used along with Equation (6-11) to predict a response PSD at various elevated locations. The response PSD was then transformed back to a response spectrum at the elevated location. For XYZ excitation the responses in a given direction were combined by SRSS.

Sample results from the above process will now be discussed. Figure 6.7-1 shows the X-direction response spectrum at location 5 for XZ excitation, and also for XYZ excitation. The results show the response spectrum that would be generated from motion at location 5 for each type of excitation. The respective response spectra also would become the RRS for subsequent testing of instrumentation to be mounted at that location. Figure 6.7-2 shows similar results for the Y-direction at location 5. The two types of testing show significant differences around 40 Hz. Referring to Table 5-1, it can be seen that this difference is caused by the Mode 3 torsion of the frame. This is further evident from Figure 6.7-3 where the response in the Y-direction near 40 Hz is shown to occur principally for the excitation in the XZ direction. These results indicate that peak response at all frequencies do occur for one or the other excitations XZ and YZ. For any functional effects that are totally amplitude dependent, the two biaxial and triaxial excitations appear to be equivalent. However, for the case where structural combined base stress due to simultaneous bending and torison may cause failure, only the triaxial test provides the correct simulation. Thus, it appears that the decision to use biaxial testing must be handled on a case by case basis, as is presently recognized.

Similar additional results are shown in Figures 6.7-4 through Figures 6.7-7. Here the proper response in the Y direction is not excited for YZ excitation, however it is excited for XZ excitation. Again, whether simultaneous response is important must be the determining factor.

In view of the above results, it appears that several observations may be summarized as follows:

1. Alignment of structural (or component) principal response axes with excitation axes is a random variable. Principal axes of an internal critical component may have any orientation relative to the externally obvious structural axes of the equipment. Therefore, one set of excitation axes is as good as another. However, some factor (i.e., 1.20) may be applied over the entire frequency range to account for this.

2. Special concern is appropriate where structurally coupled modes occur in the specimen. These occur in relatively narrow frequency bands, but may be anywhere in the seismic range. Present biaxial test procedures do not completely account for such coupling; however, this is not necessarily an invalidating factor for present tests. It depends on the degree of coupling and frequency location of the modes. Generally, separation of modes is important and the use of some excess factor can allow the results to be conservative.

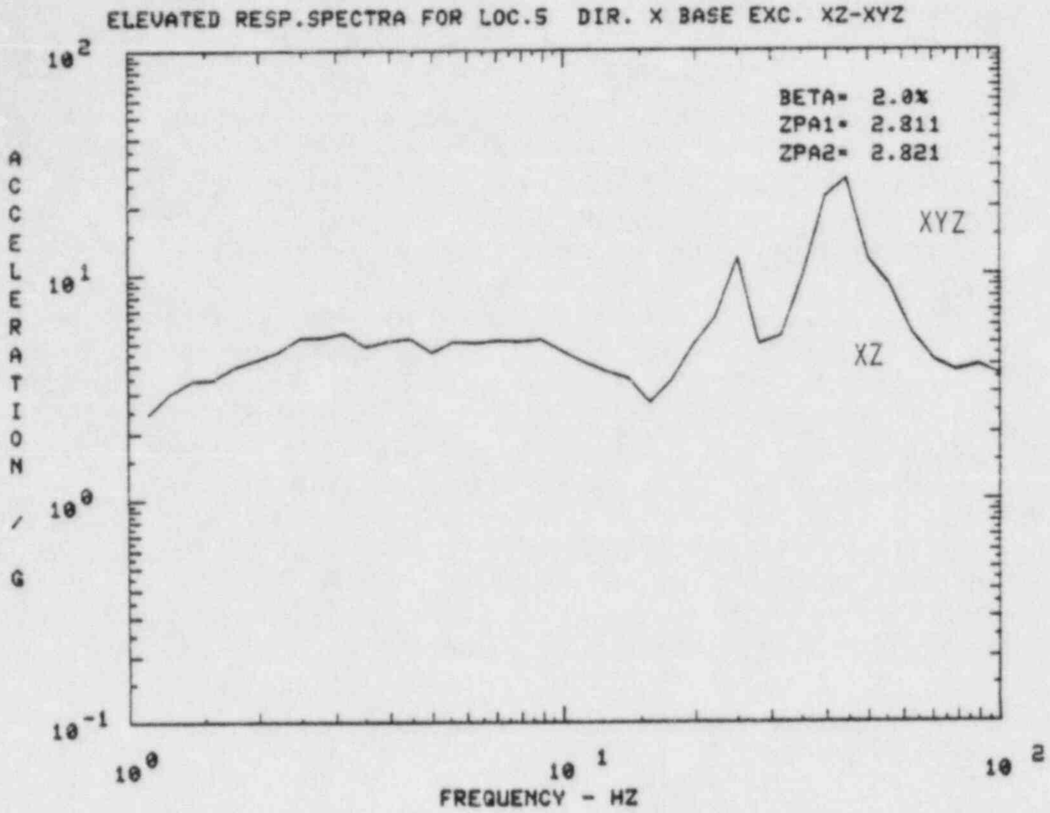


Figure 6.7-1. Response at Location 5 in X-Direction for XZ and XYZ Excitation

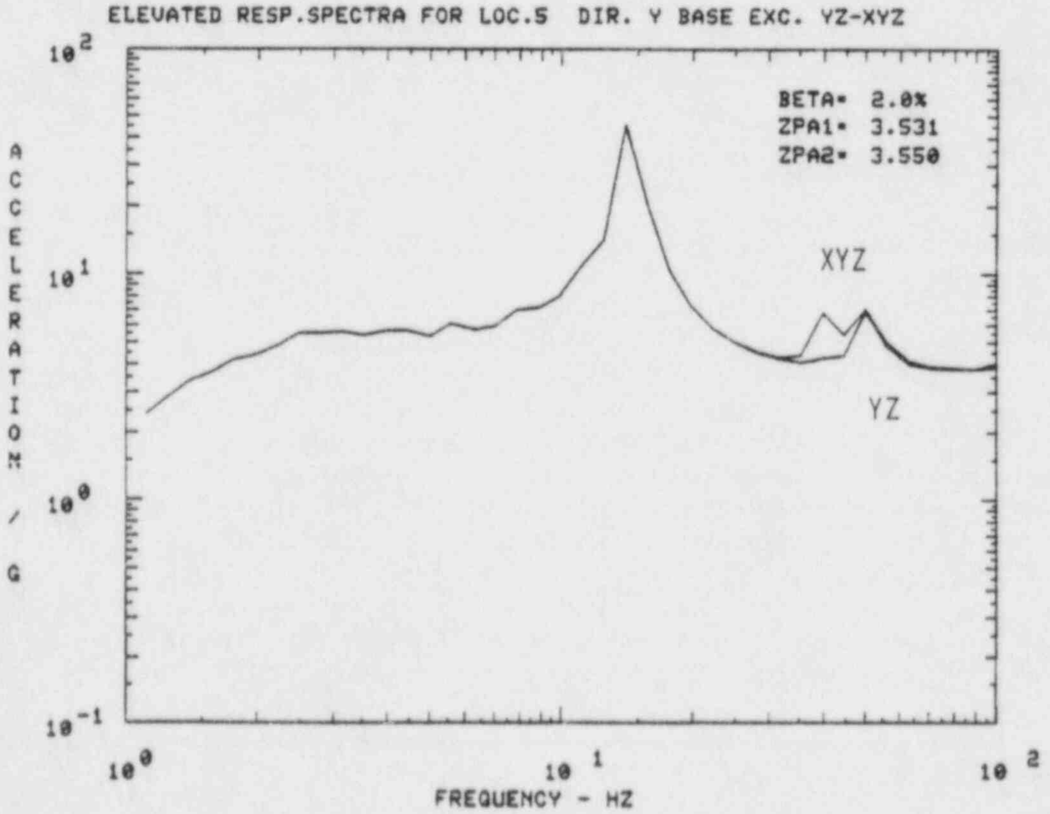


Figure 6.7-2. Response at Location 5 in Y-Direction for YZ and XYZ Excitation

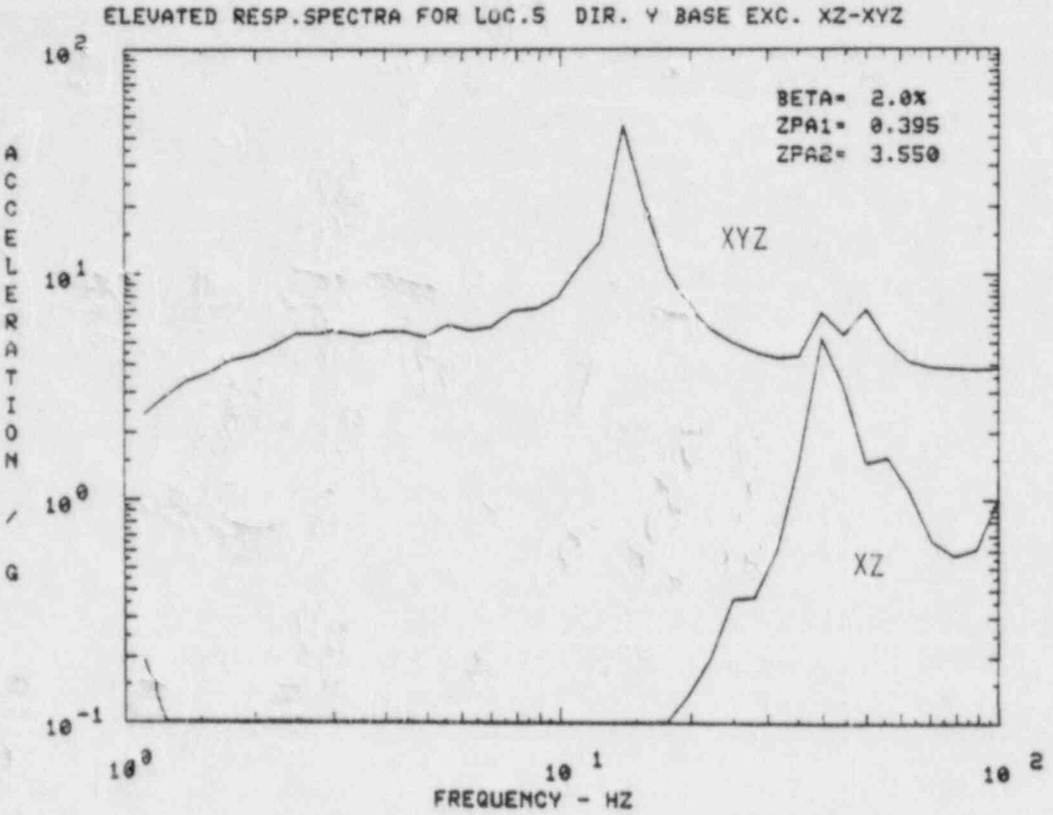


Figure 6.7-3. Response at Location 5 in Y-Direction for XZ and XYZ Excitation

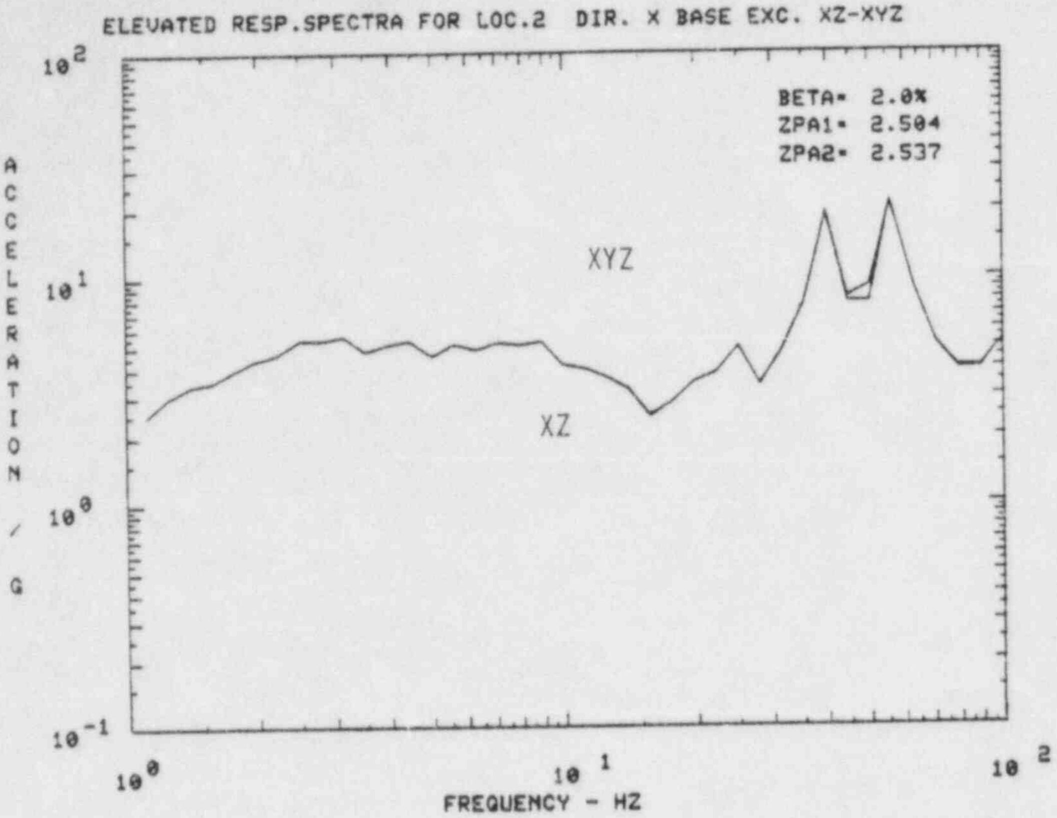


Figure 6.7-4. Response at Location 2 in X-Direction for XZ and XYZ Excitation

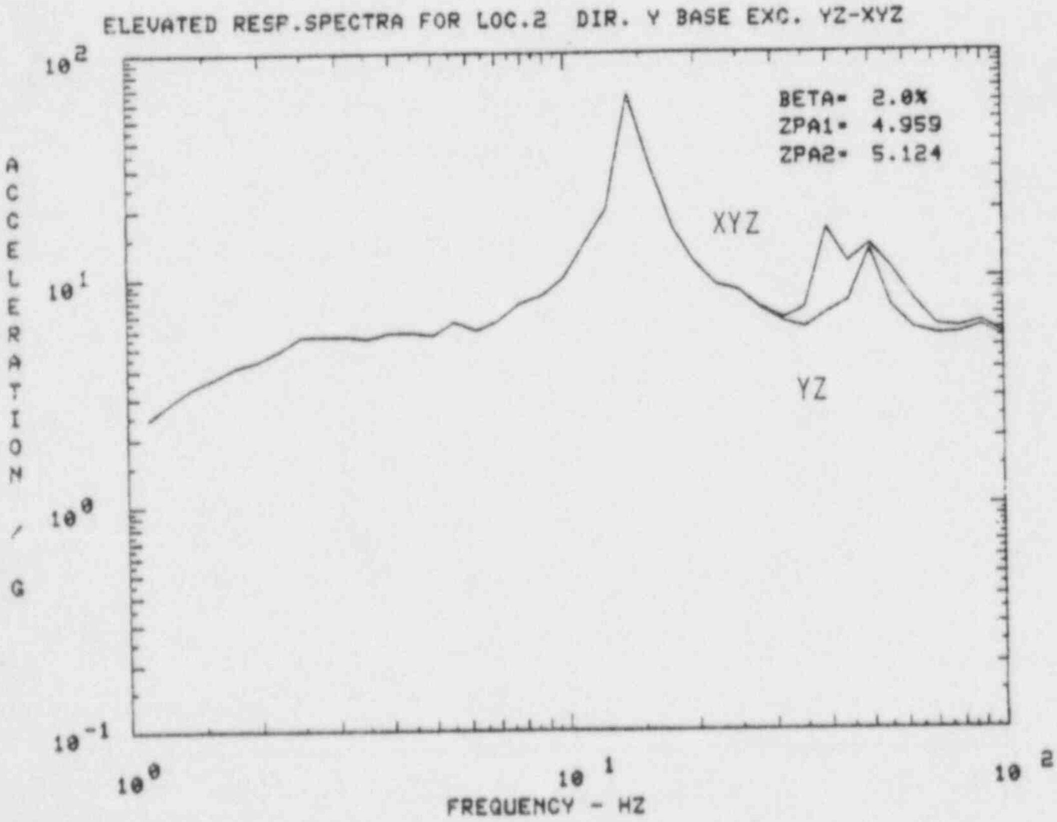


Figure 6.7-5. Response at Location 2 in Y-Direction for YZ and XYZ Excitation

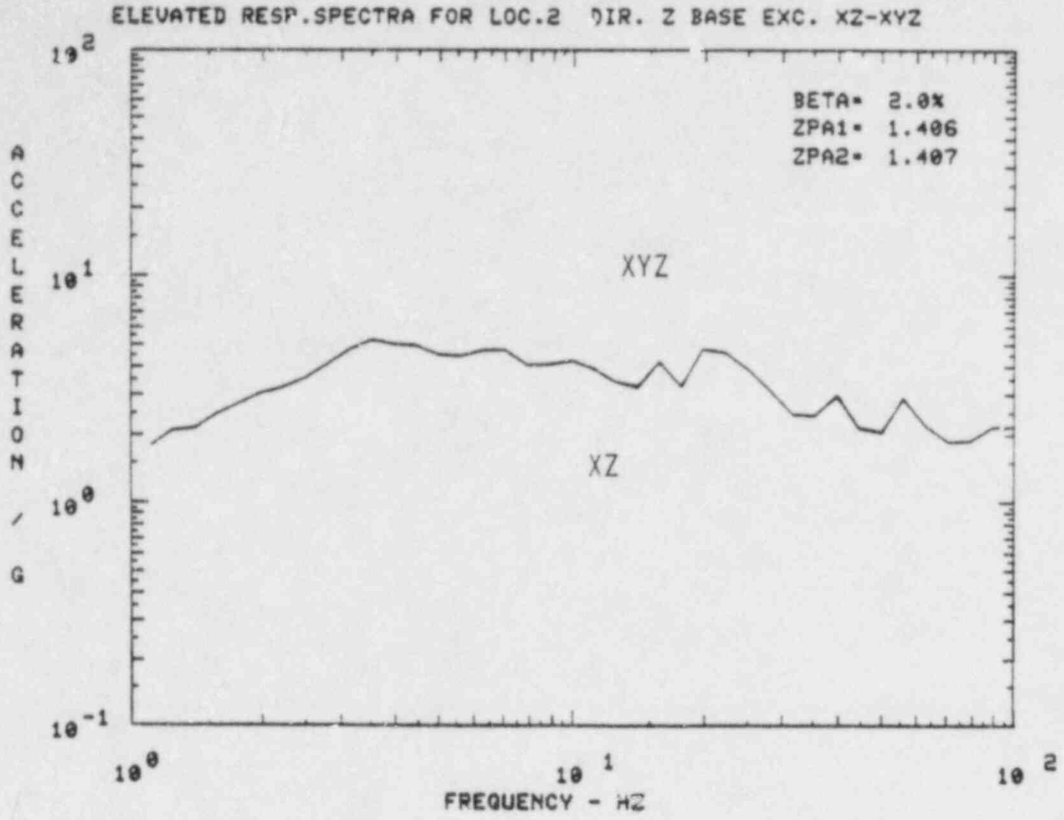


Figure 6.7-6. Response at Location 2 in Z-Direction for XZ and XYZ Excitation

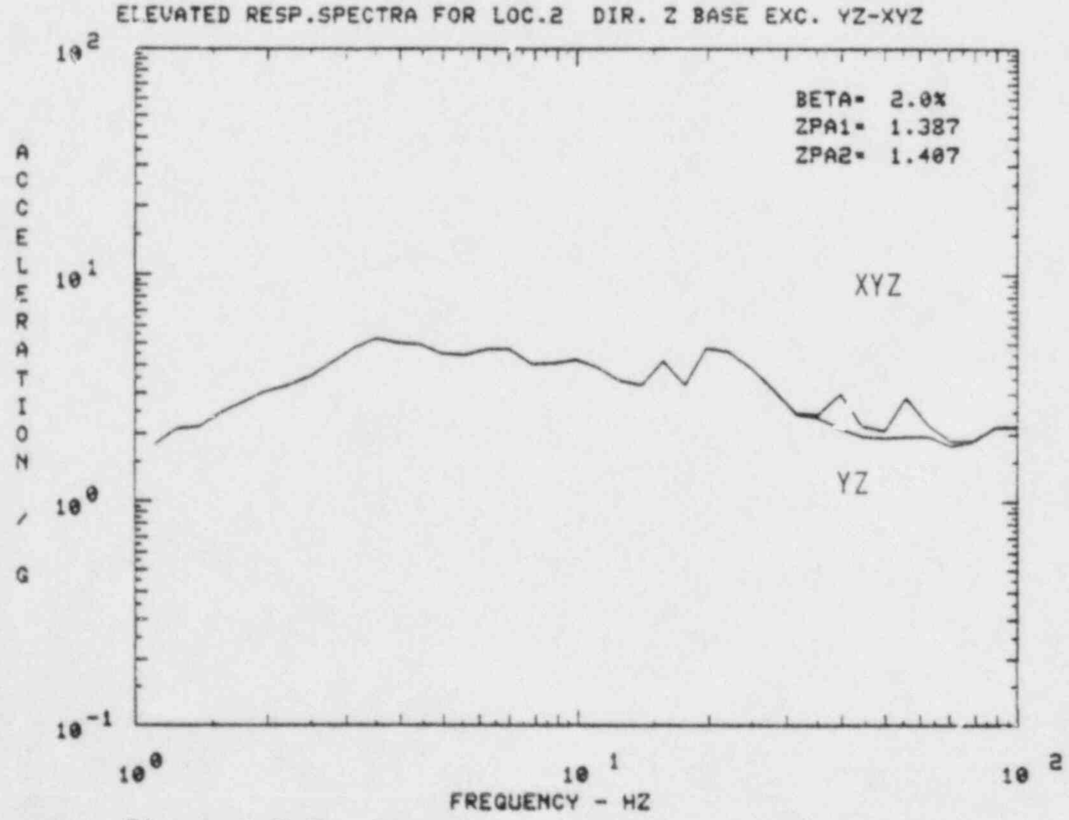


Figure 6.7-7. Response at Location 2 in Z-Direction for YZ and XYZ Excitation

3. Use of triaxial tests will not simulate coupled response where rotational inputs are present.

4. Use of multiaxis simulations (biaxial and triaxial) can introduce errors caused by base compliance. These errors can be more significant (they affect lower frequency bending modes) than those due to internal specimen coupling.

7.0 CONSIDERATIONS OF EQUIPMENT FUNCTIONALITY AND FRAGILITY

7.1 General Functionality and Fragility Concepts

As can be seen from the PREFACE to this report, the subject of fragility is to be addressed specifically in Task 4 of the current program. A measure of fragility is recognized to include a determination of the specific level of excitation parameters at which failure occurs in a specimen, and is not actually required as part of the equipment qualification process. On the other hand, functionality of a specimen at the specified excitation levels is required for qualification, and accordingly was monitored during tests conducted on the electrical rack to obtain data for the various subtasks of Task 1. Fragility and functionality are very much related, although they are basically different concepts. In effect, fragility is the uppper limit of functionality. Therefore, it is appropriate to include in this report a general discussion of fragility concepts, the results of functionality observations during tests on the electrical rack, and whatever conclusions that can be made from the data at this time. Ultimately this information will be incorporated into a more extensive study of fragility, which will be carried out and reported later under Task 4.

The subject of fragility and fragility testing for nuclear plant equipment was reviewed at length in Reference 1. It was concluded that not only has very little information been acquired from previous nuclear plant qualification tests, but there exists no universally accepted agreement on just how fragility should be measured. One of the most general descriptions of a fragility concept has been discussed by Roundtree and Safford [21], and is given in Figures 7.1-1 and 7.1-2 as a fragility surface. The idea is that failure of an item is typically related to a combination of dynamic magnitude, frequency of excitation and time. In complex assemblies many such surfaces may be possible, but the one of concern is that established by the lowest combination of parameter values. Furthermore, as shown in Figure 7.1-2, the surface is actually a statistical quantity because of various other unknowns in the process. Thus, the prediction of fragility requires some measure of the input parameters for the device, and information about the shape of the fragility surface in terms of these parameters.

A practical use of fragility in nuclear plant equipment qualification and design is acutely aggravated by the fact that many types of equipment must be considered, and various kinds of primary failures are known to occur for the equipment. Nevertheless, Kennedy et al [22] have attempted to summarize the available information for specific categories of equipment. (This list also is repeated in Section 9.0 of Reference 1.) In particular, the parameter considered most important for fragility of each category of equipment is listed. Generally, spectral acceleration (or ZPA) is given as magnitude, with frequency distribution understood. Although it was not directly listed, time is understood to be included for some items. Thus, in Figure 7.1-1, spectral acceleration or ZPA plotted on the magnitude axis, along with frequency, means that the fragility response spectrum is established in that plane. However, another approach is to establish a

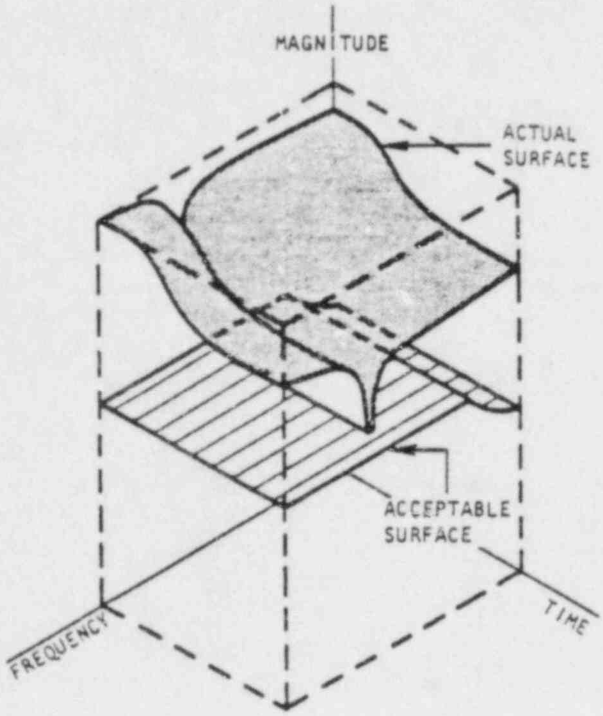


Figure 7.1-1. Comparison of Actual with Acceptable Fragility Surface

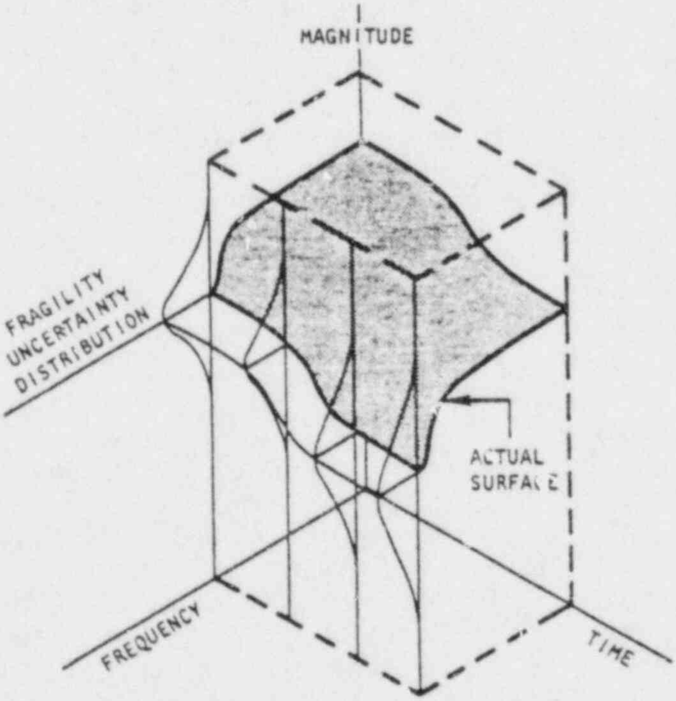


Figure 7.1-2. Actual Fragiligy Surface

steady state sine, amplitude/frequency fragility plane, or even a PSD/ frequency fragility plane.

Formation of the fragility surface generally must come from experimental data, or must be formulated according to some analytical presentation. In effect, the surface forms a fragility transfer function for the appropriate failure mechanism of a given item. Furthermore, it is understood that this function is very much dependent on the spacewise direction of the magnitude parameter (X, Y, or Z-acceleration) at face value. Thus, it would appear that much data needs to be generated and catalogued for the various equipment, before the fragility functions could be established. On the other hand, it may be possible for existing qualification data to be used as a lower bound for fragility, so that much additional data need not be generated. It is specifically this latter approach which will be pursued in the present effort. Details of these possibilities will be investigated in later tasks of the program.

Once the set of three fragility functions is obtained for a given test item they can be used to determine functionality of the device mounted on a structure. If the fragility function is divided by the structure transfer function, a site specific failure plane can be defined for the given instrument. This is then compared to the acceleration response at this location and an indication of failure obtained. Prior to use of any procedure such as this it will be necessry to perform some limited experimental and analytical investigations to determine its applicability. These investigations will also be pursued later in the program.

7.2 Fragility Study for Electrical Rack

In order to acquire at least some limited fragility data for the local panel, various functions of the four devices were monitored during performance of the test runs. Refer to Section 4.0 for a description of this setup. During the earthouake testing chatter of the electrical contacts was noted on both the Yarway and Barksdale, Table 7-1. Chatter was defined as a loss or make in contact greater than 2 msec in duration. For the Barksdale the response seemed to be primarily due to the amplitude of the excitation rather than the frequency content. The failure occurred during Runs 011 and 012 for both X-Z and Y-Z excitation. Both these runs have specified ZPA levels at 2.0 g's versus the 1.0 g's of all other runs. Typical measured ZPA's are more than twice as high, 3.53 g's horizontal acceleration for Run 011 versus 1.74 g's horizontal acceleration for Run 001. Failure of the Yarway occurred during Runs 002, 005, 006, 011 and 012. The fact that failures occurred during Runs 002 and not 001 indicates either a frequency or amplitude dependent failure. Run 002 has additional energy between 9 and 20 Hz not present for Run 001 resulting in a 15% increase in the measured ZPA. It is difficult to tell from this data whether the additional frequency content or the increased level of the ZPA induced the failure. One might be able to verify the cause of the failure with the development of a failure plane.

Failures of the Yarway also occurred during Runs 005 and 006 which had excessive low frequency and no input above 10 Hz. Although no

TABLE 7-1. SUMMARY OF FUNCTIONAL RESULTS

Type of Testing	Run No.	Axes	Failures			
			Yarway	Barksdale	Rosemount	Robertshaw
Earthquake	001	X-Z	No	No	No	No
		Y-Z	No	No	No	No
	002	X-Z	Yes	No	No	No
		Y-Z	Yes	No	No	No
	003	X-Z	No	No	No	No
		Y-Z	No	No	No	No
	004	X-Z	No	No	No	No
		Y-Z	No	No	No	No
	005	X-Z	Yes	No	No	No
		Y-Z	Yes	No	No	No
	006	X-Z	Yes	No	No	No
		Y-Z	Yes	No	No	No
	011	X-Z	No	Yes	No	No
		Y-Z	Yes	Yes	No	No
	012	X-Z	No	Yes	No	No
		Y-Z	Yes	Yes	No	No
Combined Dynamic Environment						
2-sec Burst	Earthquake	X-Z	No	No	No	No
		Y-Z	Yes	No	No	No
	Burst	X-Z	No	No	No	No
		Y-Z	No	No	No	No
	Combined	X-Z	No	No	No	No
		Y-Z	Yes	No	No	No
5-sec Burst	Earthquake	X-Z	No	No	No	Yes
		Y-Z	Yes	No	No	No
	Burst	X-Z	No	No	No	No
		Y-Z	No	No	No	No
	Combined	X-Z	No	No	No	No
		Y-Z	Yes	No	No	No
Sine Dwells		XZ&YZ	No	No	No	No
Sine Beats		XZ	No	No	No	No
		YZ	Yes*	No	No	No

*10.6 Hz with 2X & 5X pause

energy was input above 10 Hz it was induced due to rattling of the table and frame. The measured ZPA's for Runs 005 and 006 are higher, as much as 150%, than the corresponding ZPA's for Runs 001 and 002. This would indicate an amplitude dependence. This is also supported by the fact that failure occurred on Runs 011 and 012 which have the largest mesured ZPA's of all runs. One thing to note on the 011 and 012 runs is that failure only occurred for Y-Z excitation which indicates some sensitivity to the axes of excitation. This was not noted for the other runs. The difficulty in interpreting the functional results of this series of testing leads to the desirability of developing a failure plane for instrumentation groups.

Additional failures were noted for the combined dynamic environment testing. The earthquake signal was based on the standard R.G. 1.60 RRS but due to the procedures required to develop these signals additional noise was introduced into the signals not present during the initial earthquake runs. For the runs with the two second SRV burst the Yarway was the only instrument with any failures. Failures were noted for the Y-Z excitation, only for both the earthquake alone and the earthquake plus-SRV. The earthquake ZPA's were 21%, horizontal, and 44%, vertical, higher than for the initial Run 001. This may have been the cause of failure since these levels are similar to the 002 run levels. The two second SRV burst did not seem to affect the functionality. Failure of both the Yarway and the Robertshaw were noted during the five second SRV testing sequence. Both seemed to be axes dependent, Yarway Y-Z failures and Robertshaw X-Z failures. No influence of the SRV on failures could be determined.

All the instruments performed properly during the sine dwell testing. Tests were performed at both resonance and nonresonance frequencies. For nonresonance frequencies the input levels were set at both 0.1 and 0.5 g's. For excitation of resonance frequencies of the electrical panel only 0.1'g excitation was performed. No failures were noted.

The sine beat testing was performed at both resonance and nonresonance frequencies with dwells of 1/2, 2 and 5 times the beat period. The only failure noted was for Y-Z excitation at 10.6 Hz, a resonance, of the Yarway. The results again indicate that the Yarway is more sensitive to Y-Z excitation. Since no failure occurred for the sine dwell excitation, at 0.1 g's input, and did occur for the sine beats, 0.5 g's input, it is amplitude dependent.

From this series of results it can be concluded that determination of the cause of functional failures is difficult. To obtain a more complete estimate applicable to all types of events, a failure surface would need to be more clearly approximated. Details of this approach are left to later tasks of the program.

8.0 DISCUSSION AND CONCLUSIONS

Some discussion has already been provided in the various sections of this report. However, a summary of that discussion, along with some conclusions, will now be presented.

The response spectrum/power spectrum transformation has been demonstrated to be a powerful tool for use in the equipment qualification process. It can be used for purely analytical approaches, as well as in test qualifications.

A set of criteria has been established for the fundamental description of ground and elevated floor level earthquake motions. The frequency content, stationarity, coherence, and probability density of the strong motion has been established within bounds that are useful for both test and analysis purposes. The obvious use of this information is in showing whether proposed test or analysis time histories satisfy the same criteria. The exact numbers on the bounds of the parameters can still be argued, but the basic elements of the criteria have been established. Furthermore, the correspondence of other actual earthquake motions with this criteria can be additionally studied.

The initial finite element model generated from engineering drawings for the local panel provided a sufficiently accurate representation of the test item. There was sufficient correlation between experiment and analytical results to provide compatibility, although only limited coupling resulted. A primary concern of the analytical model was shown to be asociated with the support boundary condition. This appears to be the governing concern for accurate representation of the lowest bending modes.

It is also obvious that the cautions with regard to boundary conditions are extremely important for testing as well. In the present case initial judgement dictated that the steel baseplate was of sufficient stiffness, although the final results showed that it was not in the front to rear direction. These results indicate that an even greater than usual attention to the matter of base interfaces for equipment is appropriate, and if any question is present, the matter can be resolved by performing resonance searches with both fixed and table mounted conditions. This approach is especially applicable for independent biaxial or triaxial table arrangements are utilized, where specimen coupling with the table is highly likely. When such coupling occurs, adjustments to the input TRS may be necessary.

Accuracy of enveloping of the RRS by a TRS has been shown to be intimately involved with use of the correct frequency content of a test or analysis waveform. In this regard, the PSD has been shown to be much more sensitive and useful a tool, than the response spectrum, where high ZPA's tend to mask the presence of energy content. However, we do not necessarily advocate that any analysis should be supplemented with the computation of a corresponding TRS and Test PSD. On the other hand, we do conclude that some consideration of frequency content is appropriate. Concern for closer tolerances of TRS enveloping of the RRS can also solve the problem. It appears that holding the excess to no more than

20% would go a long way toward developing accurate frequency content. However, this cannot realistically be applied to the ZPA.

The results for combination of environments were somewhat surprising. In effect they indicate that SRSS of individual response spectra will provide a useful prediction of combined response spectrum for the cases studied. Signals with and without overlapping energy content were investigated.

A very useful study of in-situ modeling and subsequent analytical prediction of responses was conducted. It was shown that a variety of problems can affect the development of the analytical model from experimental data. The number and location of node points, choice of excitation method, type of computer software included, and methods of solution of the modal participation factors are some of the most important. In spite of the pitfalls, we feel that this is a viable approach to the problem of qualification of inplant equipment. However, the use of very careful attention at all steps of the process is mandatory. Successful use of the method may depend on its being implemented by only the most experienced personnel.

The need to review the question of multiaxes testing appears to have been enhanced by the results of this part of the study. However, it must be emphasized that only the presence of coupled modes appears to aggravate the problem. The use of some additional factor for each axis input for biaxial or uniaxial testing is appropriate in some cases. At this point it simply can be concluded that some type of justification appears to be important for each case. On the other hand, there is a nullifying consideration in the use of biaxial or triaxial shaker systems. As was discussed earlier, these more complex systems have more tendency to couple with a specimen and cause boundary interface problems. Unless the cautions above are observed, the gains in accuracy made with the use of independent multiaxial shaker systems can easily be nullified by inaccuracies introduced at the boundary interface.

It appears that the amplitude, frequency, and time coordinates for interpretation of a fragility surface are a feasible approach to definition of fragility in equipment and components. To implement this concept would require the determination of a fragility function for each type of equipment, either by measurements or by analytical postulation. No matter what concept is used, the lack of such data presently available is the biggest factor involved in fragility considerations. Therefore, use of existing qualification data as lower bounds for fragility may prove to be very useful. The utility of this concept will be investigated in later tasks of the program.

Finally, it should be stated that the results obtained appear to dictate even more caution in test and analysis as a means of assuring accuracy, rather than any wholesale requirement for change in methodologies. This perhaps is no surprise to most people involved with the qualification process, and have followed its developments as the art and science matures.

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ACKNOWLEDGEMENTS

The authors wish to express their sincere appreciation to several members of the SwRI staff who contributed to the conduct of this program and preparation of the reports.

Mr. D. C. Scheidt provided valuable consultation for the design and conduct of experiments. Mr. F. R. Pitman and Mr.E. Garcia provided much of the experimentation. Mr. J. H. Park provided aid with computer programming and data reduction. Mr. V. J. Hernandez provided art work for the report. Ms. R. H. Rivas, L. Ramon, H. M. Ruttan, and M. Berry all provided typing and editorial assistance.

A special note of gratitude is expressed for the efforts of the following colleagues who have served on the Peer Review Panel for this report. Their comments contributed significantly to its content.

Fred B. Safford - Agbabian Associates
Ahmad Javid - Nutech
Conway Chan - Electric Power Research Institute
Alois J. Hartman - Westinghouse Electric Co.
F. Hugh Coleman - Tennessee Valley Authority
R. Bruce Linderman - Bechtel Power Corporation
Jim Hunter - EG&G, INEL
Paul Ibanez - ANCO Engineering, Inc.
George Shipway - Wyle Laboratories
Mike Skriener - Nutech

Finally, the generous cooperation of Nutech of San Jose, California is gratefully acknowledged for providing the use of their electrical rack and several instrumentation specimens for experiments in this program.

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EVALUATION OF QUALIFICATION METHODOLOGY FOR LINE MOUNTED EQUIPMENT

by

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Report No. SwRI-6582-001-03
Contract NRC-04-81-185
Task 1 Summary Report Part III

Prepared for
U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, D.C. 20555

November 1, 1983

Approved:

Thomas A Cruse

Thomas A. Cruse, Director
Department of Engineering Mechanics

Part III

PREFACE

This report represents one of a series which is to present the results of a research program that is being conducted to evaluate methodology of equipment seismic qualification for nuclear plants. The overall program consists of the following subtasks:

1.1, 1.2, 1.3	Review methodology, aging, and static loads; Identify anomalies
1.4	Evaluate multiple frequency excitations
1.5	Consider combined dynamic environments
1.6	Develop in-situ test criteria
1.7	Study procedures for line mounted items
1.8	Publish Task 1 Summary Report
2.1, 2.2, 2.3	Investigate response level and multiple-parameter correlations
2.4, 2.5	Consider single-parameter and damage severity factor correlations
2.6	Develop general correlation method
2.7	Publish Task 2 Summary Report
3.1	Recommend updating of qualification criteria
3.2	Publish Task 3 Summary Report
4.1, 4.2	Compile fragility data
4.3	Evaluate and reduce data
4.4	Publish Task 4 Summary Report

Specifically, this document constitutes the Task 1 Summary Report, Part III, and it presents the results from Task 1.7 listed above. Other reports and papers previously published under other tasks are listed as References 1-7 on the list given at the end of this report. Work on Task 4 is in progress, and will be reported in the last-indicated summary report.

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1.0 INTRODUCTION

1.1 Overview

The evaluation of waveforms for seismic testing of nuclear plant equipment has been one of several objectives of this research program. A complete evaluation of typical waveforms for most types of tests was previously conducted and reported in References 2 and 4. However, because of the special nature of waveforms required for simulation of the line-mounted dynamic environment, as well as other problems peculiar to this application, a separate subtask was assigned to this part of the study. The results of this work are reported herein.

Current methodology [1] for testing line (pipe) mounted items has included sine dwell or sine beat type motions. The philosophy for their use includes the assumption that such motion conservatively represents a near resonance response of a lightly damped piping system to earthquake excitation. On the other hand, other motions, such as narrowband random, appear to be a more suitable representation of a lightly-damped, resonant system responding to broadband earthquake motion. Therefore, a comparison of these several waveforms has been performed in this study. For convenience, a linear analog circuit was first used to represent a lightly-damped system, and its responses to several waveforms were studied. Then, similar responses were observed in a typical valve specimen. Subsequently other problems, such as cross-axis coupling, were also evaluated.

1.2 Existing Test Requirements

The dynamic environment for devices mounted on piping systems is typically narrowband in frequency, with an amplitude determined by the spatial location relative to the vibrational modes of the piping system. Actually, a good representation of the excitation is known to be a narrowband random waveform, with center frequency at the resonance of the piping system. Early simulations of this environment included sine dwells, with later simulations specified as sine beats [8,9]. Of course, a major problem associated with the simulation is that the exact frequency of the piping system may not be known or may vary from one installation to another. As a result, current guidelines require that a series of uniaxial sine beats be applied, with center frequencies spaced at 1/3-octave intervals over the frequency band, and at any resonance identified in an initial resonance search. The amplitude of the beats is usually based on predictions from some form of dynamic analysis of the piping system. Operation of the device is required during the most conservative beat series, which usually is one applied at a resonance condition.

The above procedure has been developed principally for valve operations, but has generally been adapted to line mounted items in general. It has been used principally for seismic qualification. However, other dynamic environments, such as safety relief valve (SRV) discharge and loss of coolant accidents (LOCA), are known to include higher frequency motion. Therefore other considerations have been given to this type of simulation. One method for qualifying valves under these conditions has been reported by Bhargava, et al. [10].

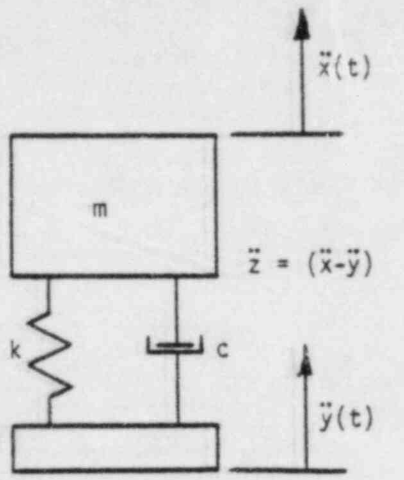
2.0 ANALOG COMPUTER SIMULATION

2.1 Typical Waveforms and Responses

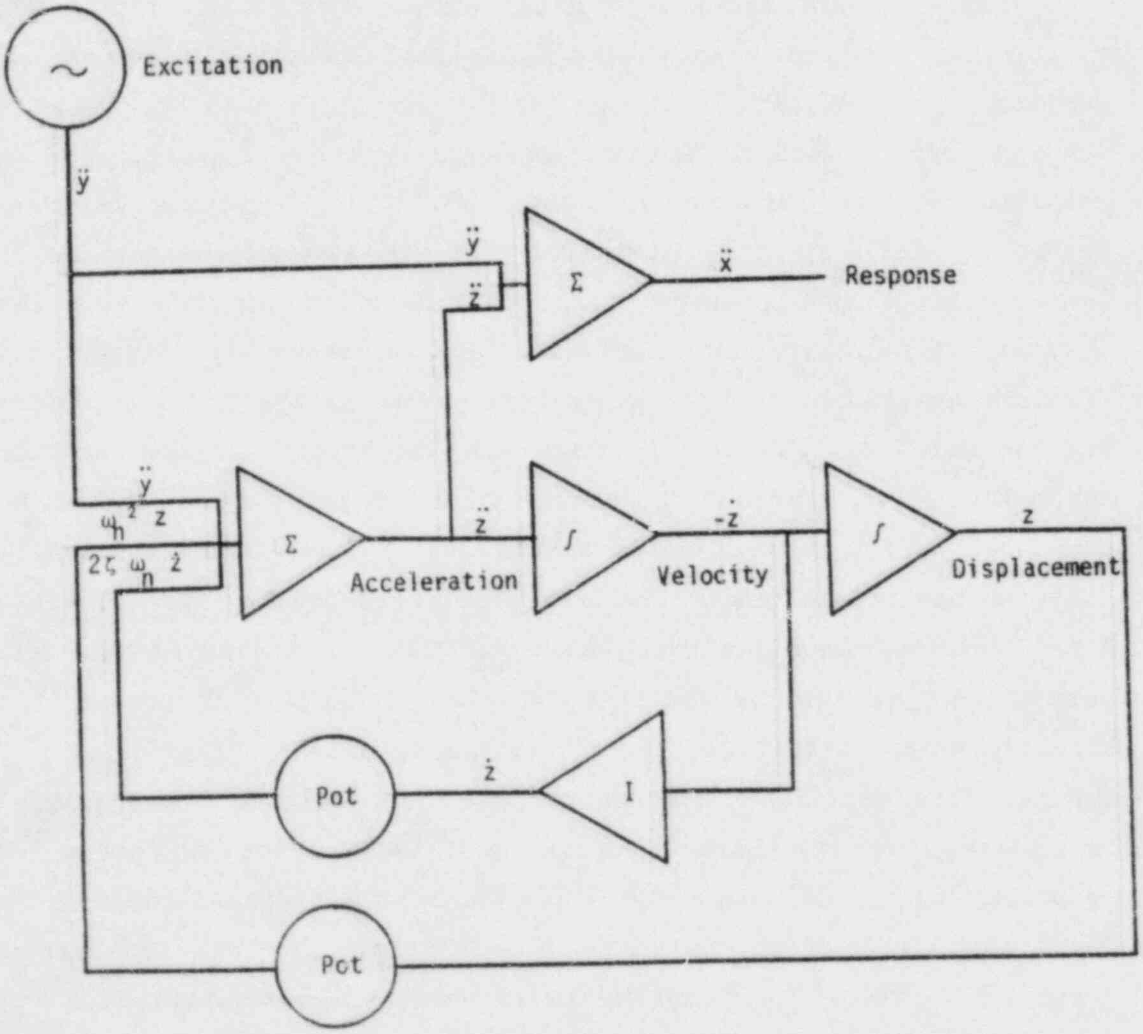
A single degree of freedom oscillator was designed to represent a single mode of a piping system, which was ideally excited by a variety of typical waveforms. The response of this oscillator to the different motions was evaluated in terms of its adequacy to represent the intended dynamic environment. A schematic of such an oscillator is shown in Figure 2.1-1. For most data runs, the natural frequency was set near 10 Hz (mid-seismic range) and the damping was varied over several lightly-damped values representative of piping systems. Synthesized excitation and response waveforms were recorded on analog tape for subsequent data processing.

Figure 2.1-2a shows a typical ground level excitation waveform, which nearly matched the Reg. Guide 1.60 response spectrum for 2% damping. The signal level was ramped up in 5 seconds, held for 15 seconds (strong motion) and decreased to zero in 10 seconds. A sample response waveform of the oscillator to this excitation is shown in Figure 2.1-2b. The broadband nature of the excitation is shown in the corresponding Power Spectral Density (PSD) of Figure 2.1-3a, while the predominantly narrowband response PSD is shown in Figure 2.1-3b. Similar data is shown for a narrowband random excitation and response in Figures 2.1-4 and 2.1-5. In this case the excitation was generated by narrowband filtering of a random noise source, whose amplitude was modulated by the same envelope as the Reg. Guide 1.60 earthquake. Note that the amplifications of the narrowband response in Figures 2.1-3b and 2.1-5 are only qualitative, since a 0.94 Hz analysis bandwidth is insufficient to resolve the peak value at 2% damping of the oscillator. Finally, a set of excitation and response is shown in Figure 2.1-6 for a typical sine beat waveform applied at the oscillator resonance. For this case, the oscillator damping was adjusted so that decay of the response would just occur for a one beat pause between beats. It was found that this condition could be maintained for any combination of damping and frequency if the following equation was satisfied:

$$f \; T_p \; \zeta = 0.5$$

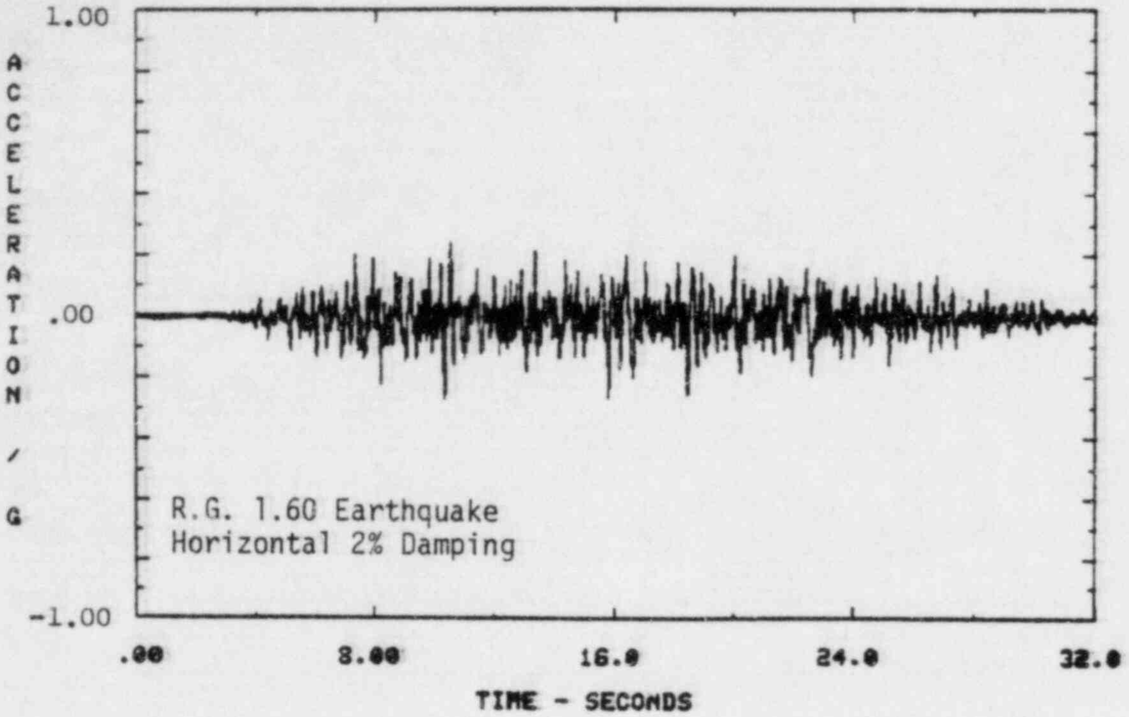


a) Single-Degree-of-Freedom Oscillator

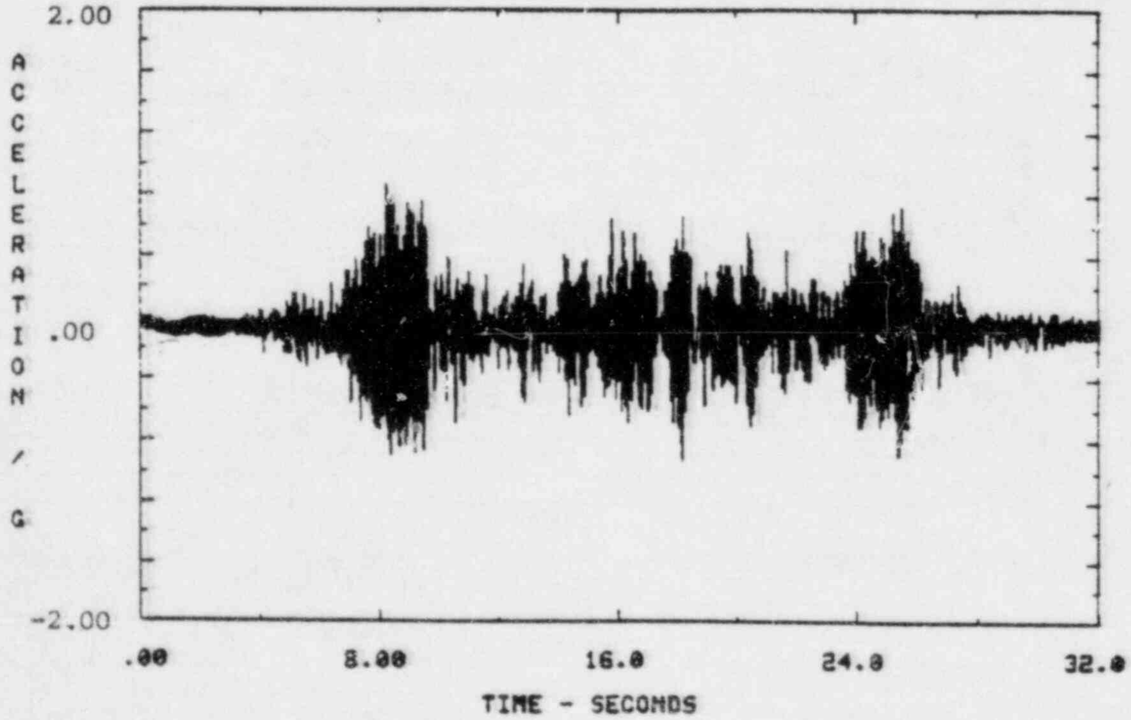


b) Analog Simulation

Figure 2.1-1 Analog Computer Simulation of a SDOF Oscillator

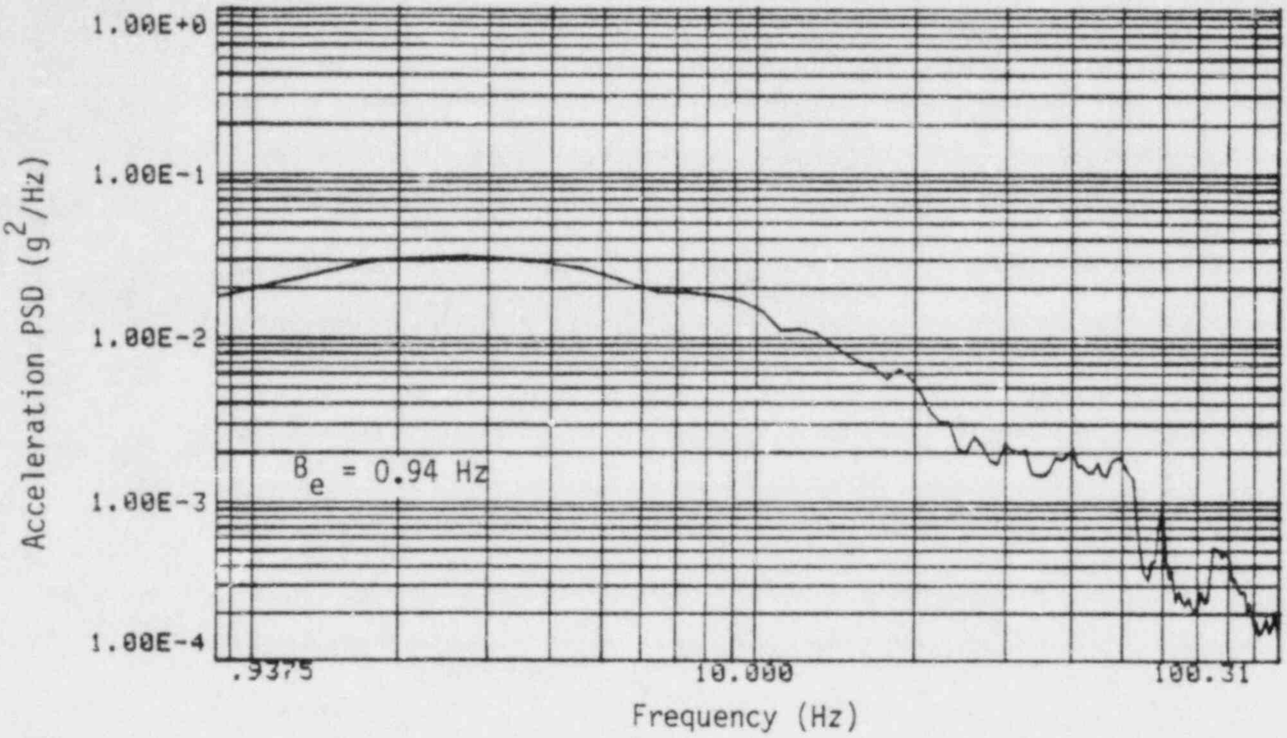


a) Excitation Waveform

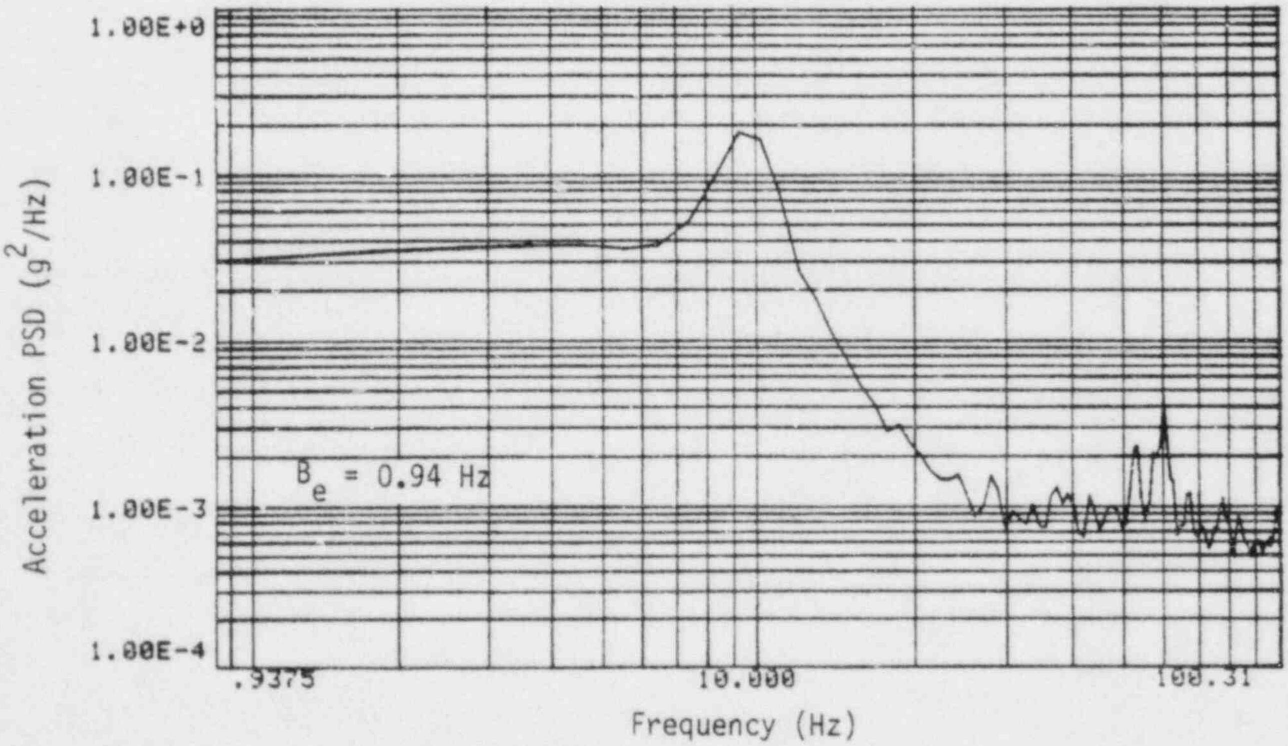


b) Oscillator Response Waveform
SDOF, 9.92 Hz, 2% Damping

Figure 2.1-2 SDOF Oscillator Response to Broadband Random Excitation

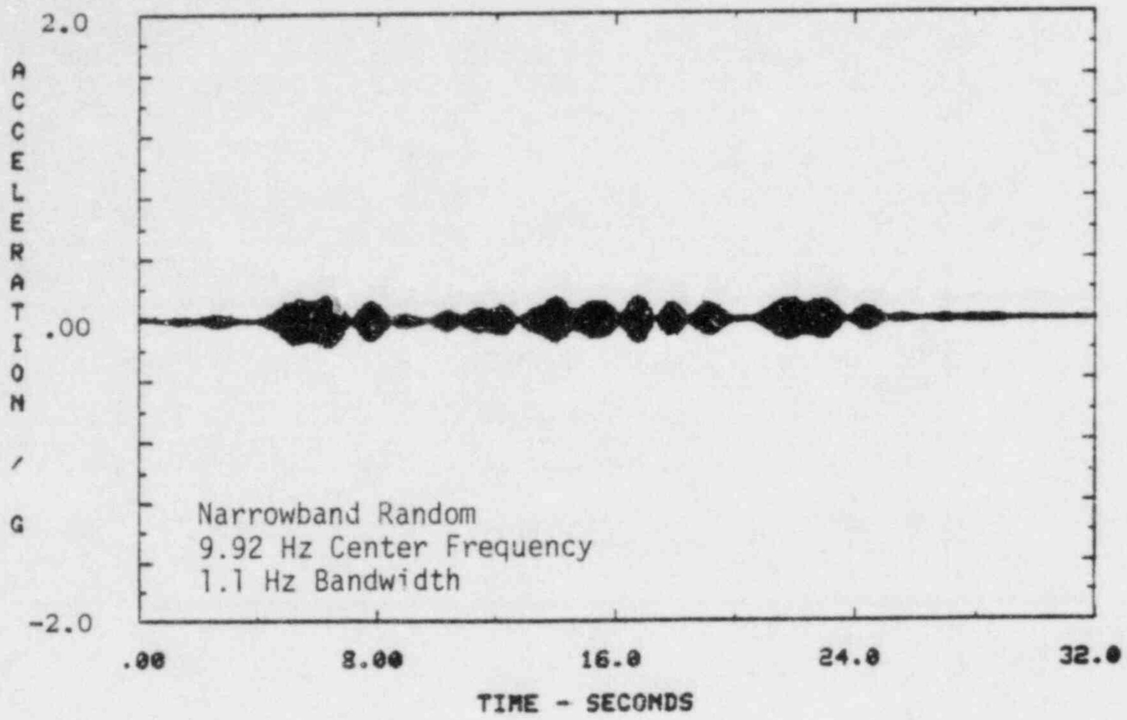


a) Input R.G. 1.60 Earthquake
Horizontal 2% Damping

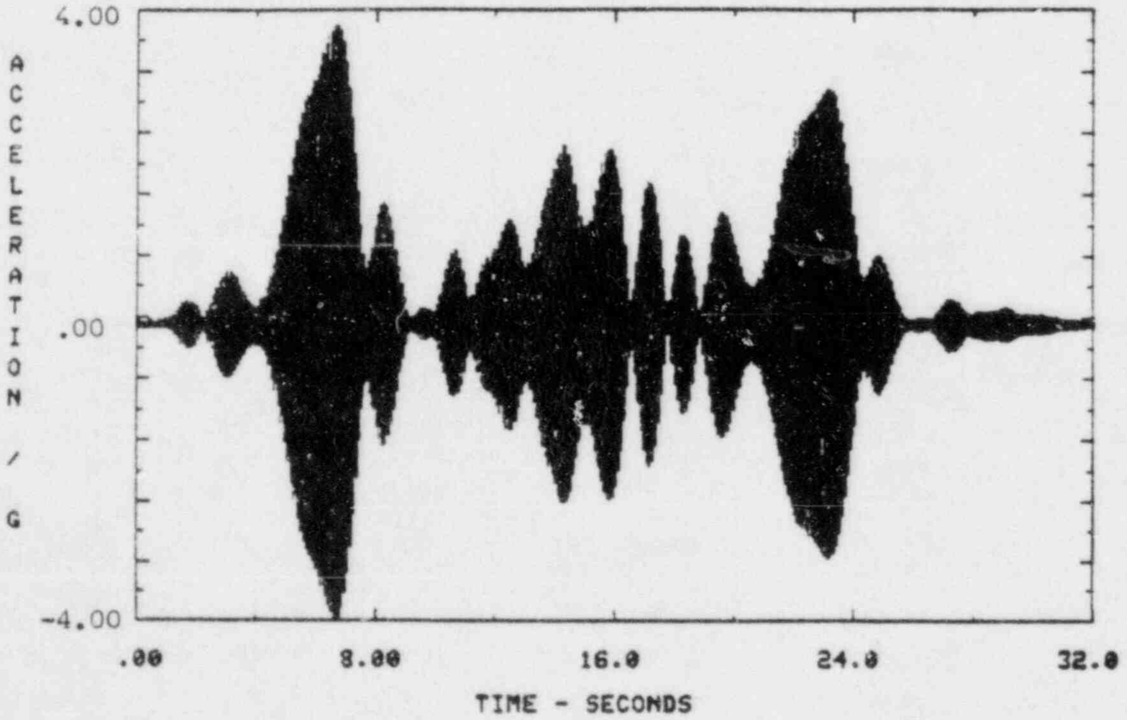


b) Response SDOF Oscillator at 9.92 Hz
and 2% Damping

Figure 2.1-3 Input and Response PSD to a R.G. 1.60 Earthquake

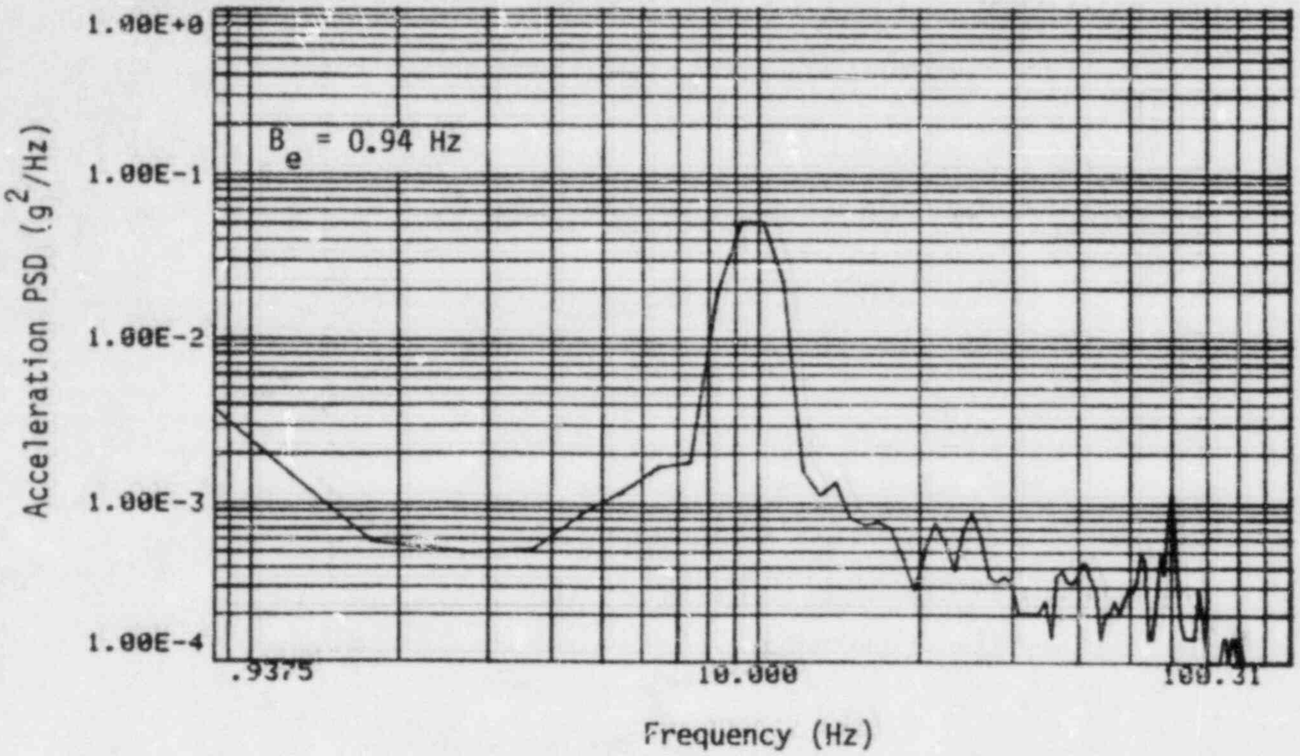


a) Excitation Waveform

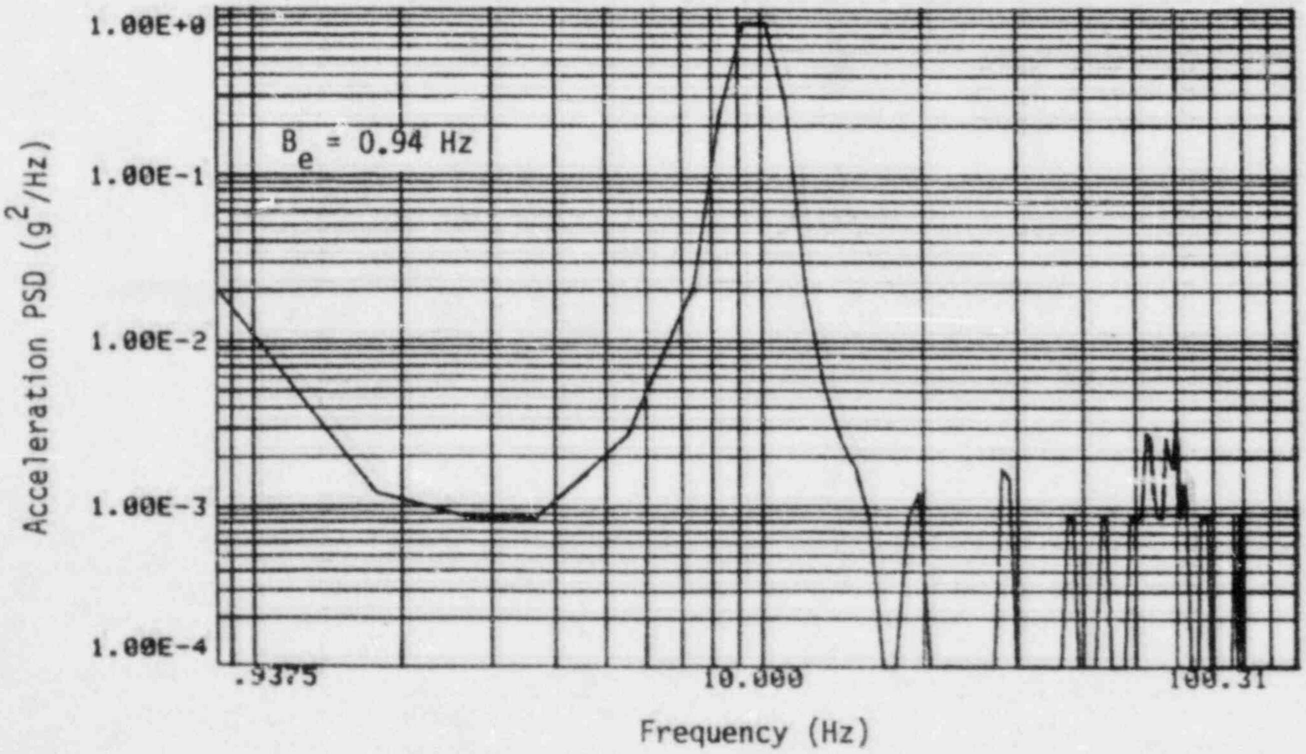


b) Oscillator Response Waveform
SDOF, 9.92 Hz, 2% Damping

Figure 2.1-4 SDOF Oscillator Response to a Narrowband Random Excitation

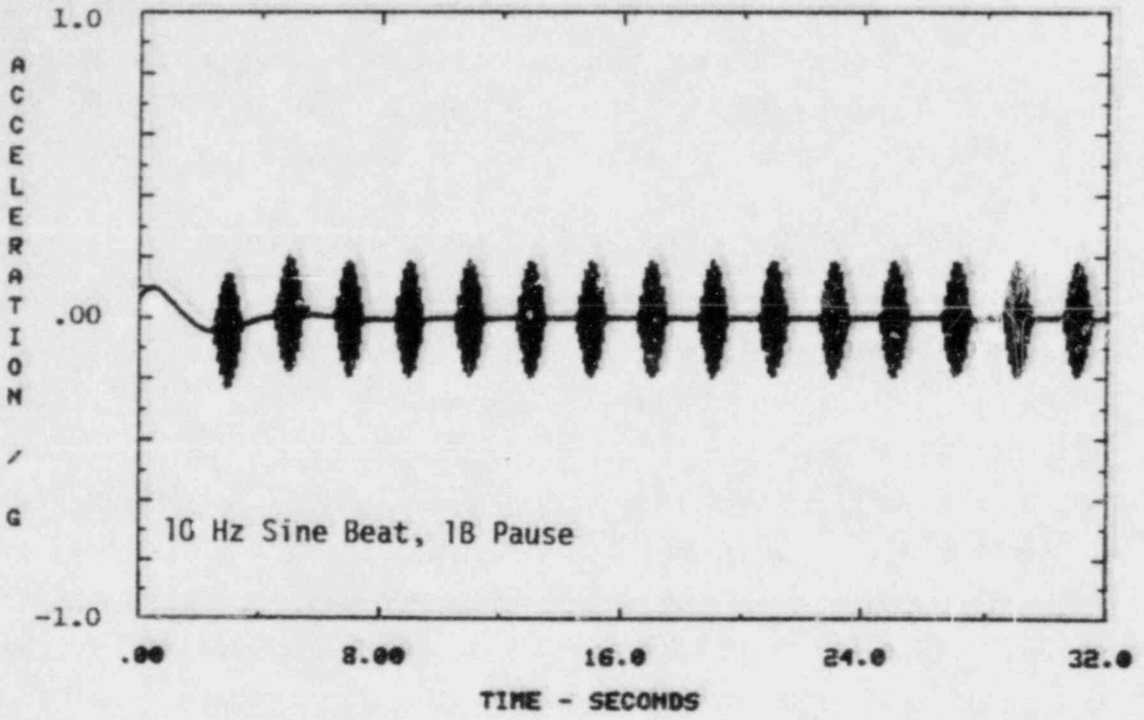


a) Input - Narrowband Random 9.92 Hz Center Frequency and 1.1 Hz Bandwidth

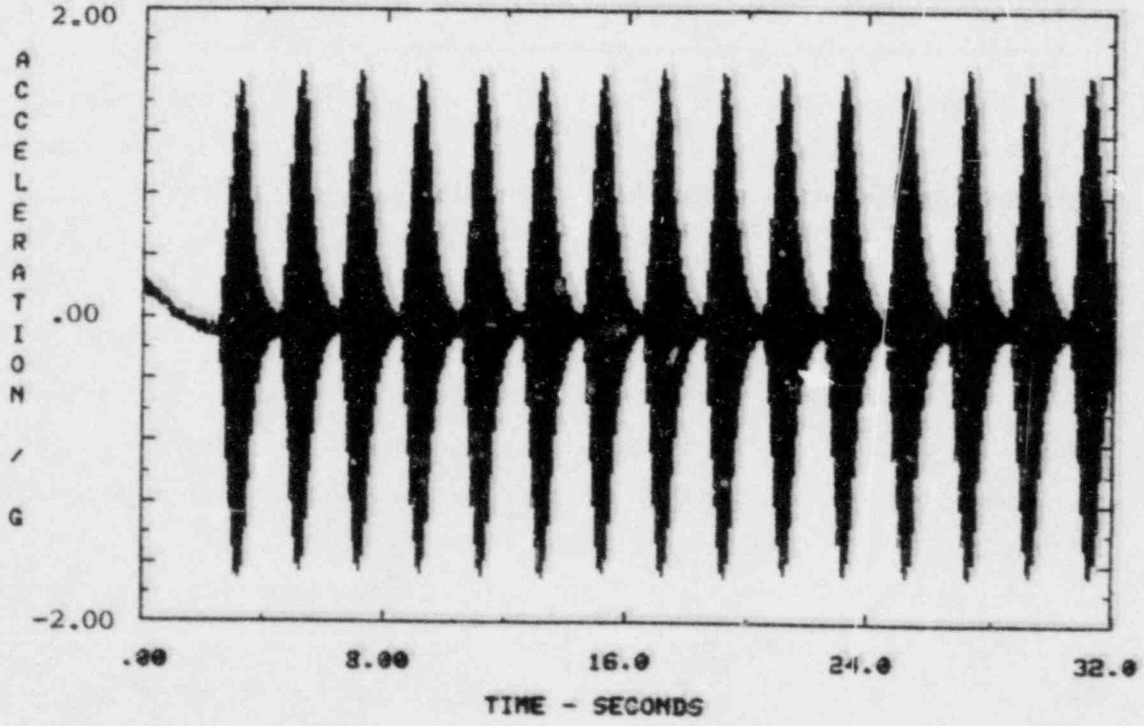


b) Response - SDOF Oscillator at 9.92 Hz and 2% Damping

Figure 2.1-5 Input and Response PSD to a Narrowband Random Signal



a) Excitation Waveform



b) Oscillator Response Waveform
SDOF, 10 Hz, 5% Damping

Figure 2.1-6 SDOF Oscillator Response to a Sine Beat Excitation where f is the oscillator frequency in Hz, T_p is the pause (or beat) length in seconds, and ζ is the critical damping ratio.

For all of the above figures the analog voltages were rescaled to represent acceleration amplitudes for the excitation $\ddot{y}(t)$ and the response $\ddot{x}(t)$ in Figure 2.1-1a.

2.2 Comparison of Response Characteristics

The objective of this study was to evaluate the effects of the waveform on the oscillator response, and to interpret the results in terms of the adequacy of test procedures for seismic qualification of equipment. A summary of various waveform runs and characteristics of the excitation and response data is given in Table 2-1. Data are given in terms of various peak and RMS amplitude ratios. In all cases the RMS value is measured over the majority of the event, rather than just the strong motion portion for those signals that include ramp up and ramp down regions. Therefore peak/RMS ratios for random signals will be somewhat higher than 3.0, which is generally considered an upper limit for signals having a Gaussian instantaneous amplitude distribution [2,4]. From the two right-hand columns it can be seen that the peak ratio for output/input tends to be more severe for the random signals, while the RMS ratio is more severe for the sine beat signals.

Additional analyses of the data are given in subsequent figures. Figure 2.2-1 shows the probability density function for peak amplitudes for the narrowband random output of the oscillator (Figure 2.1-2) which results from the broadband input. It can be seen that the distribution is approximately Rayleigh, which would be expected when the instantaneous amplitudes are Gaussian. Note that these data are computed from the strong, motion portion of the waveform, as defined in Reference [2,4]. Some nonstationarity is still present, so that the computed probability density is shifted somewhat to the right, compared to the Rayleigh distribution.

Figure 2.1-4 shows that the oscillator output was also narrowband random when the input was narrowband random. This input waveform has not been used in the past, but it appears to be potentially a very useful possibility, since it is easily generated in the laboratory, and produces the correct simulated response in the oscillator. The

TABLE 2-1
PEAK AND RMS AMPLITUDE RATICS FOR EXCITATION AND RESPONSE

Excitation Waveform	Oscillator Frequency	Oscillator Damping	Peak/RMS*		Output/Input Ratio	
			Input	Output	Peak	RMS
R.G. 1.60 Earthquake Horizontal 2% Damping	9.92	0.02	3.42	3.67	3.61	2.89
Narrowband Random 9.92 Hz Center Frequency 1.1 Hz Bandwidth	9.92	0.02	2.88	4.19	20.81	14.11
10 Hz Sine Beat No Pause	10.0	0.02	1.99	1.63	15.12	18.41
10 Hz Sine Beat 1 B Pause	10.0	0.01	2.81	1.83	18.36	28.15
	10.0	0.02	2.81	2.18	13.07	16.81
	10.0**	0.05	2.80	2.58	7.57	8.21
	10.0	0.10	2.82	2.64	4.33	4.54
	10.5	0.02	2.78	2.29	11.64	14.13
10 Hz Sine Beat 2 B Pause	10.0**	0.02	3.34	2.63	12.55	15.97
10 H Z Sine Dwell	10.0	0.01	1.42	1.41	49.21	49.58
	10.0	0.02	1.42	1.41	24.98	25.21
	10.0	0.05	1.43	1.41	9.81	9.93
	10.0	0.10	1.43	1.41	4.80	4.85
	10.5	0.02	1.43	1.41	24.30	24.62

Data from 0.25 Hz to 50.0 Hz.
*4 samples or 20 seconds of data.
**Nearly complete decay during pause.

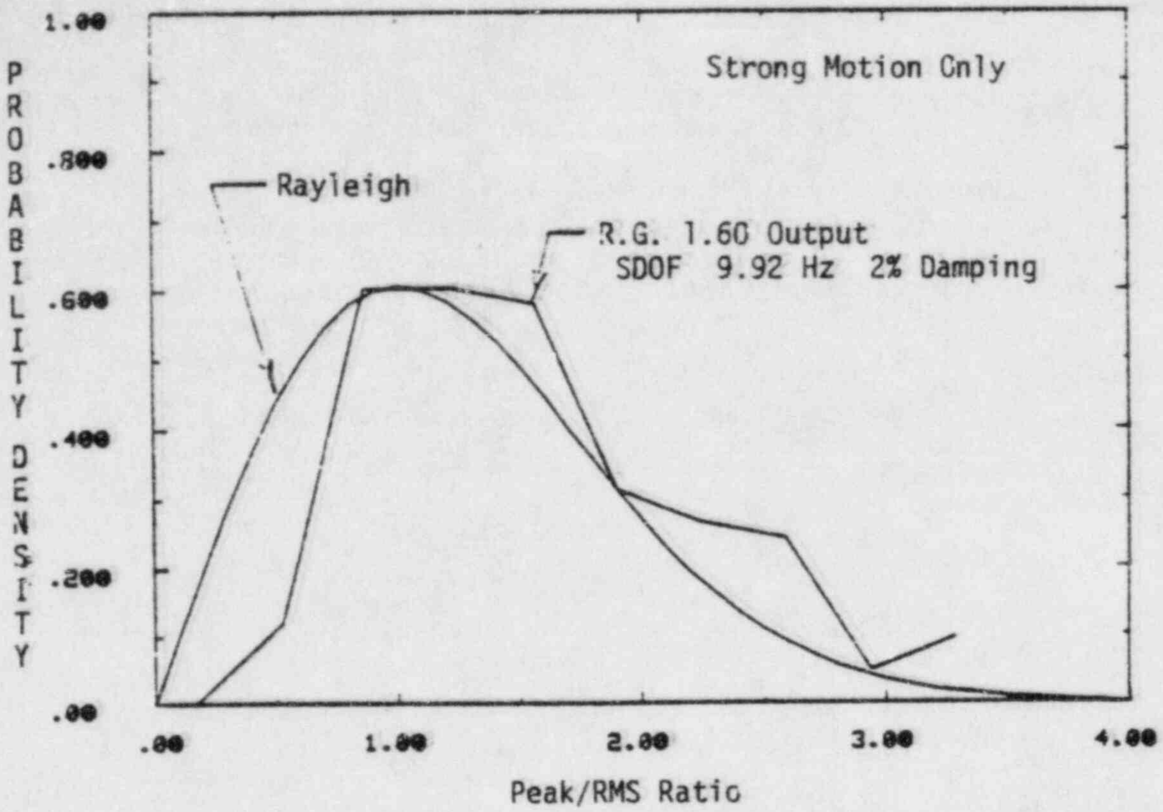


Figure 2.2-1 Peak Probability Density for Simulated Earthquake Response

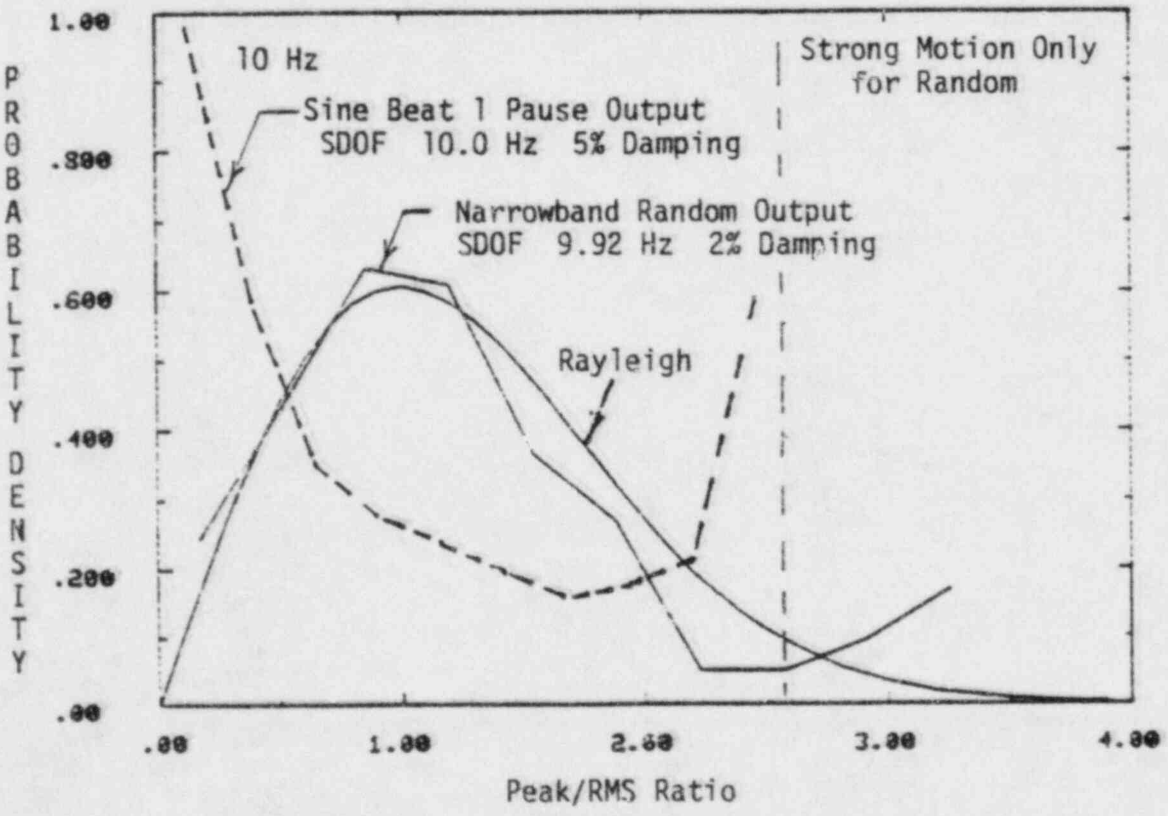


Figure 2.2-2 Peak Probability Density for Various Waveform Responses

probability density for the peak amplitudes of the strong motion portion of this signal is given in Figure 2.2-2 and appears to be essentially a Rayleigh distribution. It is further compared to the distribution for the peak amplitudes of the sine beat response, whose waveform appears in Figure 2.1-6. Numerical data for generating these curves is given in Table 2-2. It can be seen that the probability density functions for the narrowband random and decaying sine beat waveforms are significantly different.

The above-described differences in probability density and in peak and RMS ratios immediately provokes a question about the significance of this result. It appears that the answer to this question lies in the physical mechanism that governs failure or malfunction in a given piece of equipment. For example, if the failure is governed by peak amplitude excitation, then the narrow band random waveform would appear to be more severe. If it is governed by RMS amplitude, then the sine beat would appear to be more severe. On the other hand, if it is governed by accumulated counts of amplitude at various levels (such as in fatigue), then it is not apparent as to which waveform is more severe.

In order to shed light on the fatigue issue a further analysis was performed. Figure 2.2-3 shows a graphical relationship for the number of fractional cycles necessary to obtain one equivalent peak cycle, as a function of percent of maximum peak cycle amplitude. This curve was generated from a log log-amplitude v/s number of cycles fatigue plot, with an exponential factor of 2.5. It is currently being considered for inclusion in a revision of IEEE 344. It is argued that the plot can be used to determine the accumulative fatigue equivalence of two different waveforms. Therefore, this curve was used to develop a fatigue potential comparison for the narrowband random and decaying sine beat response waveforms, when the total duration of strong motion is 15 seconds. The numerical data are given in Table 2-3. For each case, the peak/RMS amplitude abcissa of Figure 2.2-2 was divided into increments of 0.2. The number of cycles in each increment is therefore

$$n_i = (p_i)\ (0.2)\ (15)\ (f_c)$$

where p_i is the average value for the probability density in the increment and f_c is the center frequency for the narrowband motion (or sine beat). The percent of maximum peak amplitude is obtained from

TABLE 2-2
AMPLITUDE PROBABILITY DENSITIES FOR
RAYLEIGH AND SINE BEAT DISTRIBUTIONS

Range	Amplitude (Probability Density)	
Peak/RMS Ratio	Rayleigh	Sine Beat
0-0.2	0.10	1.00
0.2-0.4	0.29	0.71
0.4-0.6	0.44	0.47
0.6-0.8	0.54	0.34
0.8-1.0	0.59	0.28
1.0-1.2	0.60	0.25
1.2-1.4	0.56	0.22
1.4-1.6	0.49	0.19
1.6-1.8	0.41	0.16
1.8-2.0	0.32	0.17
2.0-2.2	0.24	0.20
2.2-2.4	0.17	0.36
2.4-2.6	0.11	0.65
2.6-2.8	0.07	
2.8-3.0	0.04	
	4.97	5.00
	x 0.2 = 0.99	x 0.2 = 1.00

TABLE 2-3
EQUIVALENT NUMBER OF PEAK CYCLES IN RAYLEIGH AND SINE BEAT WAVEFORMS

Center Frequency = 10 Hz
Time Duration = 15 sec
10 Cycles/Beat, 1 Beat Pause

	Rayleigh				Sine Beat			
Range Peak/RMS Ratio	No. Cycles n_i	% Max. Peak Amplitude	Frac. Cycles per Peak Cycle	No. Equiv. Peak Cycles	No. Cycles n_i	% Max. Peak Amplitude	Frac. Cycles per Peak Cycle	No. Equiv. Peak Cycles
0-0.2	3.0	3.3	>400	---	15	3.8	>400	---
0.2-0.4	8.7	10.0	300	---	10.6	11.5	200	0.1
0.4-0.6	13.2	16.7	70	0.2	7.1	19.2	65	0.1
0.6-0.8	16.2	23.3	32	0.5	5.1	26.9	26	0.2
0.8-1.0	17.7	30.0	20	0.9	4.2	34.6	13	0.3
1.0-1.2	18.0	36.7	12	1.5	3.8	42.3	8.5	0.5
1.2-1.4	16.8	43.3	8	2.1	3.3	50.0	5.8	0.6
1.4-1.6	14.7	50.0	5.8	2.5	2.8	57.7	4.0	0.7
1.6-1.8	12.3	56.7	4.2	2.9	2.4	65.4	3.0	0.8
1.8-2.0	9.6	63.3	3.2	3.0	2.6	73.1	2.2	1.2
2.0-2.2	7.2	70.0	2.6	2.8	3.0	80.8	1.8	1.7
2.2-2.4	5.1	76.7	1.9	2.7	5.4	88.5	1.8	3.0
2.4-2.6	3.3	83.3	1.6	2.1	9.8	96.2	1.2	8.2
2.6-2.8	2.1	90.0	1.4	1.5				
2.8-3.0	1.2	96.7	1.2	1				
			Total	23.7			Total	17.4

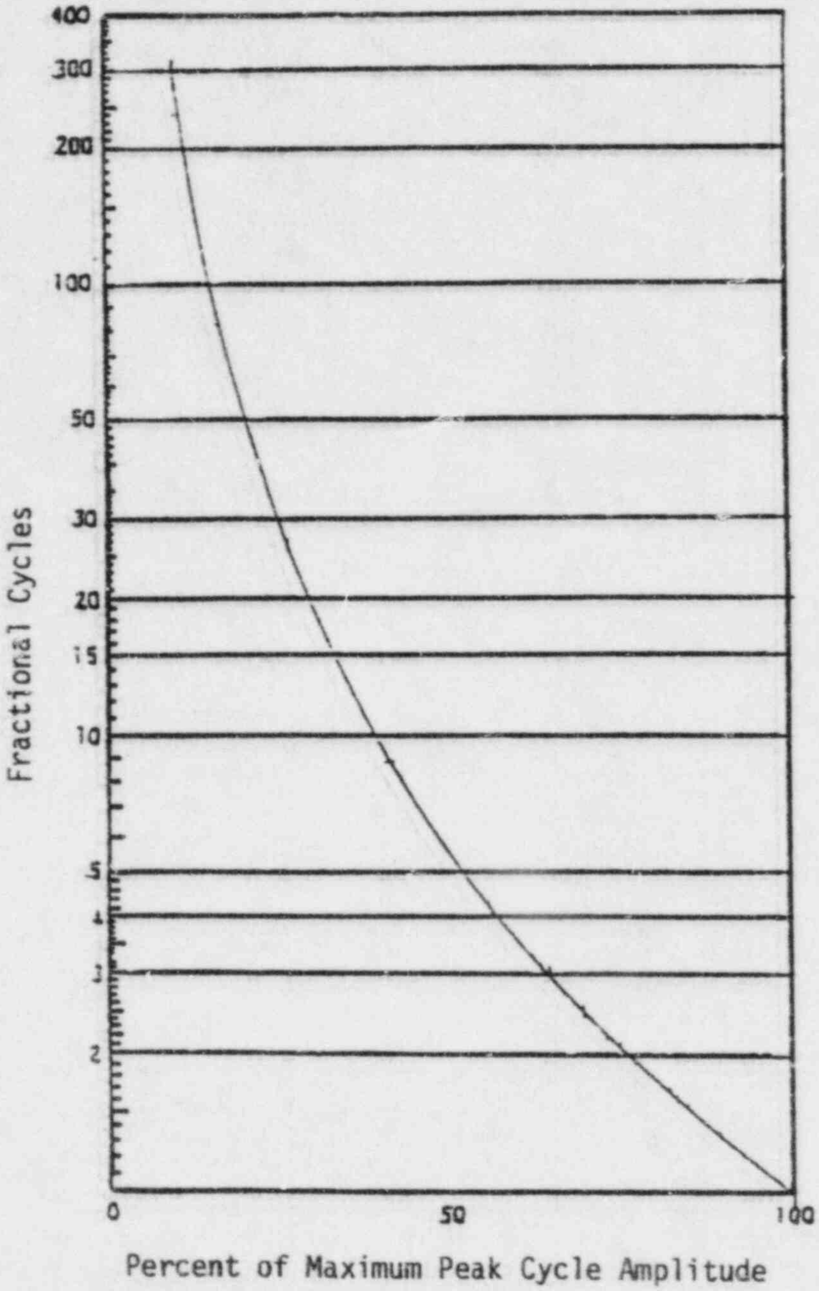


Figure 2.2-3 Fractional Cycles to Obtain One Equivalent Maximum Peak Cycle

the ratio of the value of peak/RMS in the given increment to the maximum value. The number of fractional cycles per peak cycle for the increment is obtained from Figure 2.2-3 at the respective percent of maximum peak value. Finally, the number of equivalent peak cycles for each amplitude increment is obtained by dividing the number of cycles n_i by the respective number of fractional cycles per peak cycle. By totaling this last column for each respective waveform, a quantitative comparison of fatigue potential can be made. This comparison is valid directly, providing that the waveforms have equal peak amplitudes. From Table 2-3 it can be seen that the two response waveforms are approximately equal, with the narrowband random (Rayleigh) being somewhat more severe.

If the peak values of the two waveforms are different, then Figure 2.2-3 can also be used to get an equivalent number of peak cycles to allow for this difference as well. For example, if the two waveforms had equal RMS amplitudes, then the random waveform would have a peak factor

$$3.0/2.6 = 1.15$$

greater than the sine beat. In this case its equivalent number of peak cycles would be

$$23.7\ (1.6) = 37.9$$

for the narrowband random waveform. Note that the 1.6 is obtained from Figure 2.2-3 at a percent of maximum peak cycle of

$$1/1.15 = 0.87$$

In this case, the narrowband random waveform appears to be significantly more severe.

3.0 MOTOR ACTUATED VALVE

3.1 Test Item Description

To complement the analog computer simulation a test program was developed and implemented for a typical valve specimen. The test item consisted of a globe valve with actuator mounted to a section of pipe, Figures 3.1-1 and 3.1-2. This test item was attached to two types of mounting fixtures to simulate a "rigid" and "flexible" support condition. The bookends in turn were mounted to the seismic simulator for excitation along the horizontal and vertical axes of the test item.

The valve is a four inch class 1690 globe stop valve with an electrical actuator. The stem is inclined with respect to the normal flow line by 45°, to reduce flow disruption and pressure loss across the valve. Gearing on the actuator was such that the closing and opening times were approximately 1[illegible] seconds. This allowed for operation of the valve during the simulated seismic events. An electronic controller was used to open and close the valve during all testing.

Nominal four-inch diameter pipe was welded to the valve body to allow for attachment to the bookends and pressurization of the valve. The ends of the pipe were capped with end caps that had tapped holes for pressurization. During the majority of testing the valve was pressurized to 1000 psia using water and a Sprague pump. This allowed for a means of measuring leakage before, during, and after the test. Prior to testing, the limit and torque switches in the actuator were adjusted so that no leakage occurred while the valve was closed.

3.2 Mounting Configuration

Two mounting configurations, test item to bookends, were used during the test sequence (Figure 3.2-1). The "rigid" configuration was designed to simulate typical mounting used during seismic qualification testing. Valves supplied for tests usually have bolted flanges welded to the body. These are then attached to bookends to allow for support and pressurization during test. The "rigid" supports used during the tests described herein consisted of welded two-inch thick steel bookends with V-blocks used to clamp the pipe in place. A four-inch long section of angle was placed on the V-block to distribute the force over a length

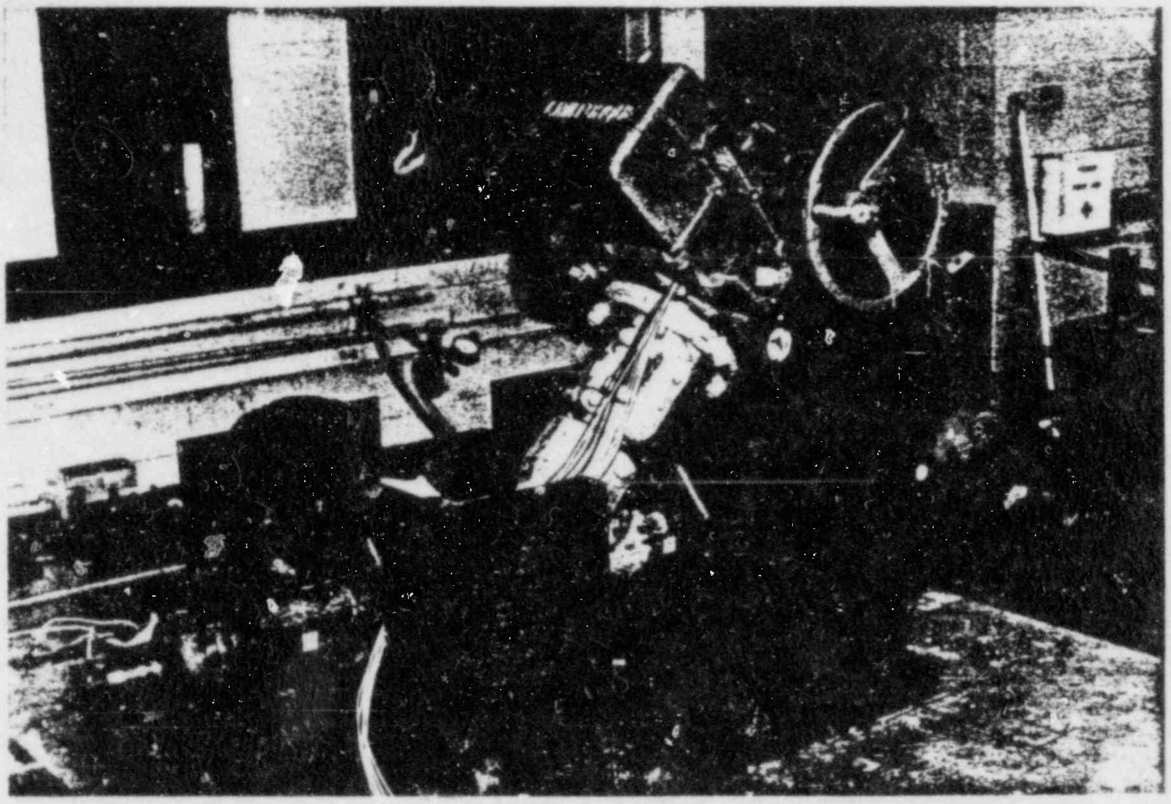


Figure 3.1-1 Globe Valve on Rigid Bookend

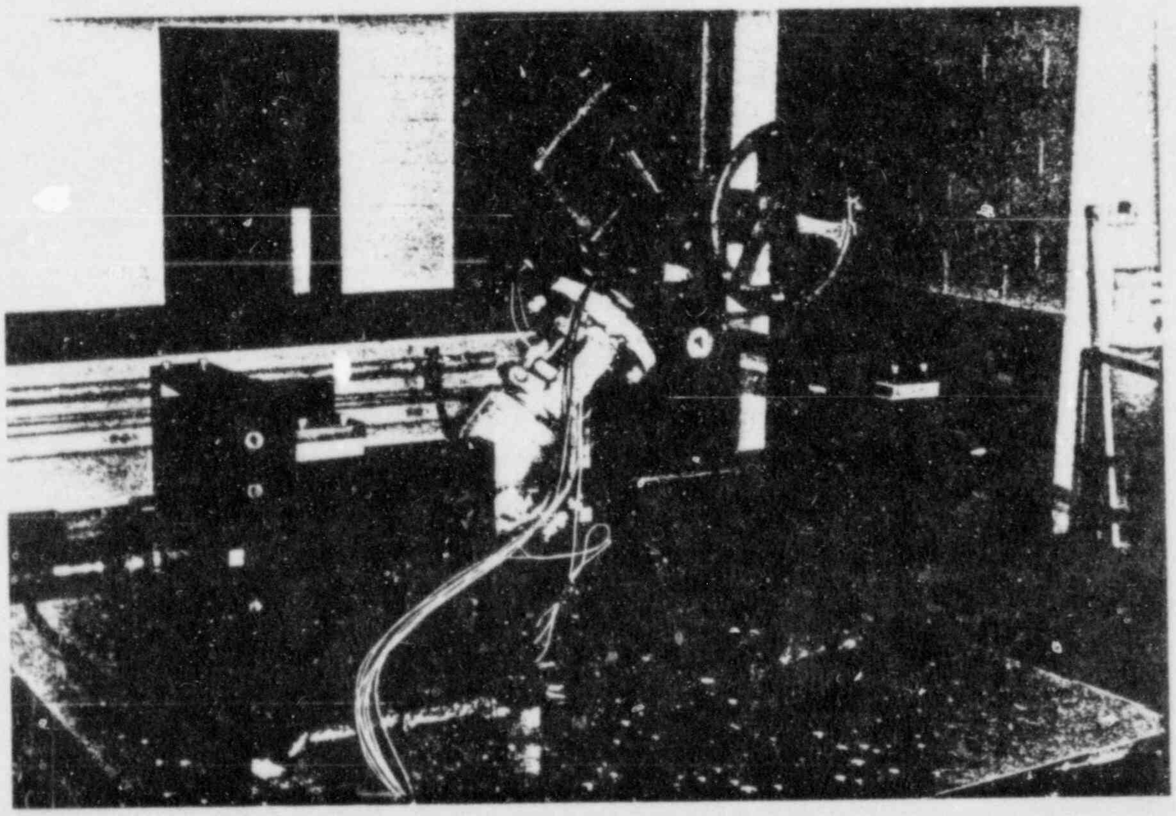
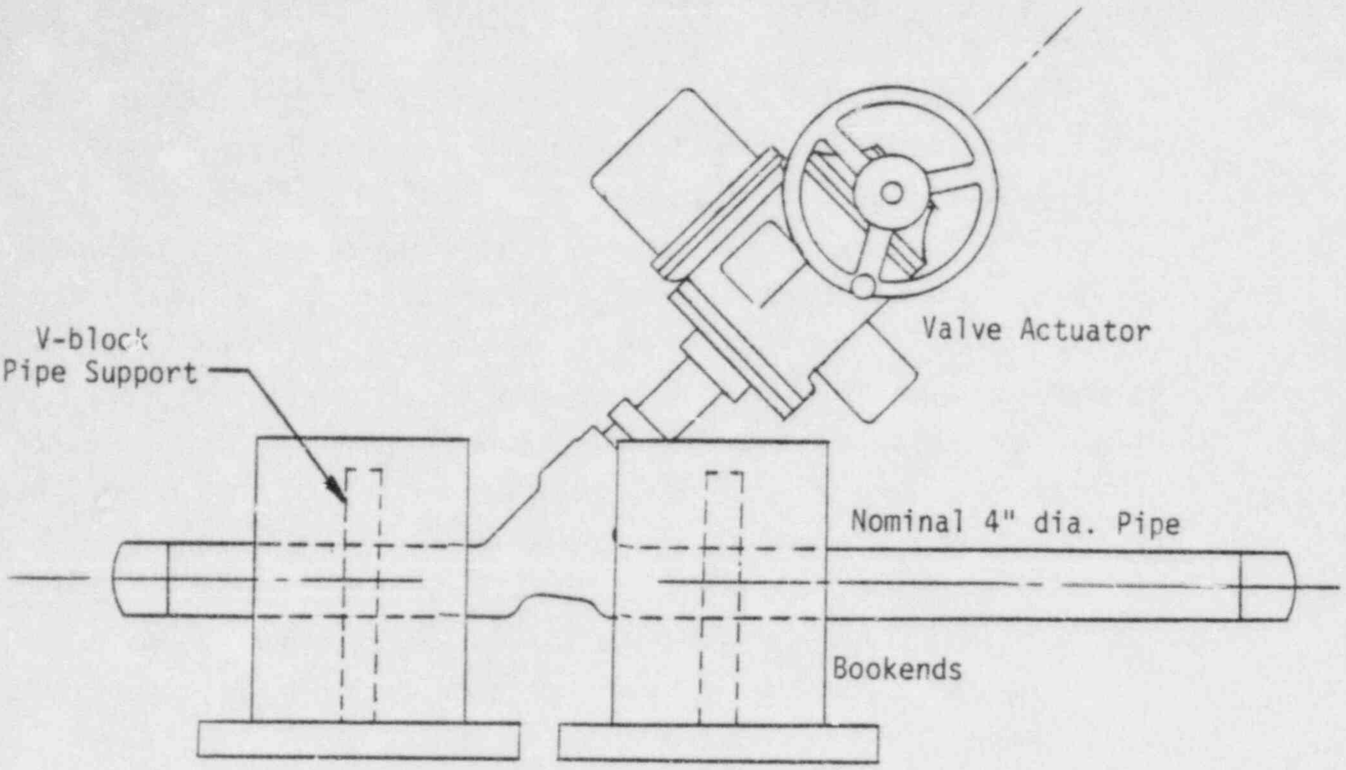
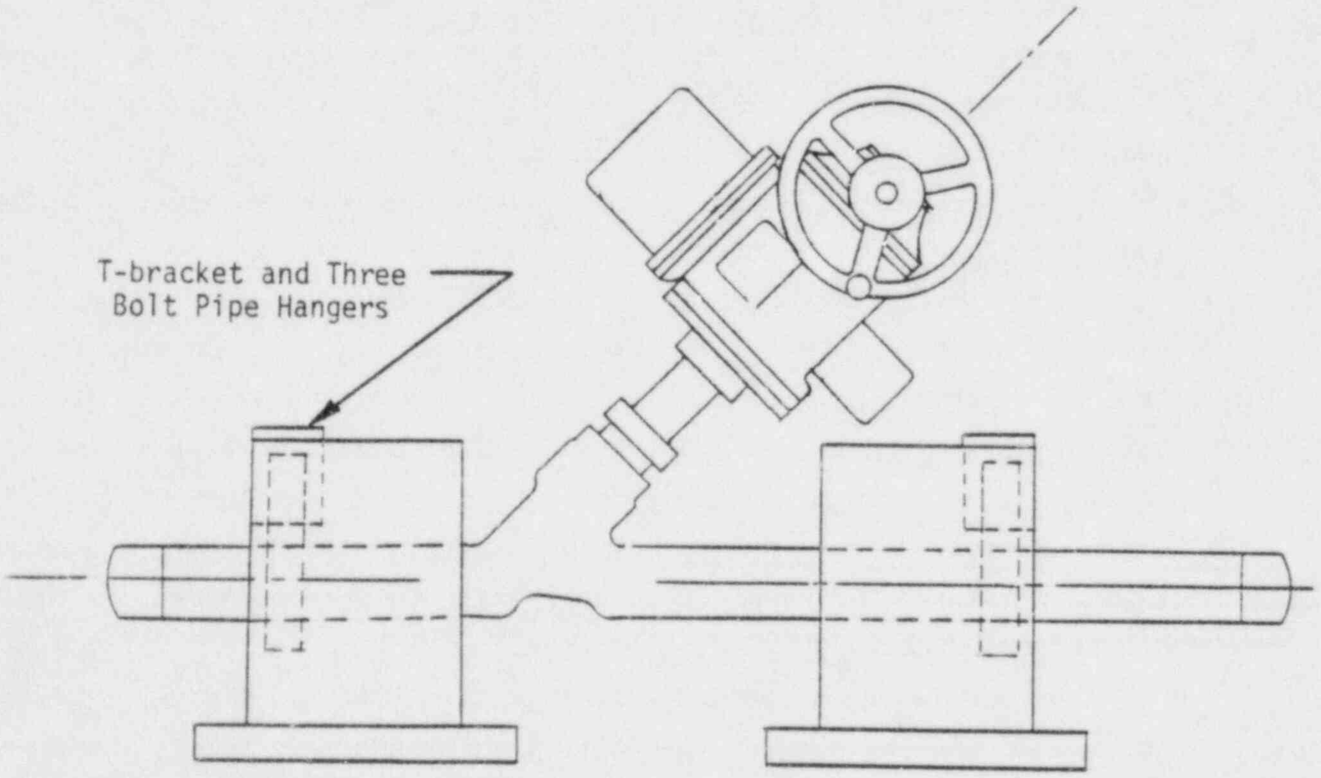


Figure 3.1-2 Globe Valve on Flexible Support



a) Rigid Supports



b) Flexible Supports

Figure 3.2-1 Valve Mounting Configurations of pipe and prevent pitching of the test item. The distance between the V-blocks was designed to match the distance between bolted flanges used on this type valve. During the tests it was determined that this configuration did provide a reasonable approximation of rigid mounting.

The flexible mounting was designed to simulate an in-service condition rather than the rigid test condition. Rather than being clamped in the V-blocks, the pipe was hung using a three-bolt pipe clamp. By moving the bookends and support points the distance between centerlines of the supports was increased to 41 inches. The three-bolt pipe clamp was attached to the bookend using a welded steel T. The thickness of the T was 3/4" to provide some vertical flexibility. The design of the mounting fixture allowed for both horizontal and vertical motion of the pipe. No attempt was made to match any specific in-service condition. However, a flexible support which included coupling in the seismic frequency range was provided.

3.3 Instrumentation

Instrumentation was designed to obtain information on the response characteristics of the valve and its functional state. Seven accelerometers were used during the testing sequence. Two were used to monitor the horizontal and vertical accelerations of the table input. The other five were placed at various locations and orientation on the test item to provide the required response information. For the structural identification tests three accelerometers were mounted on a block to provide triaxial acceleration measurements. For the impact hammer structural identification tests, measurements were made at the locations shown in Figure 3.3-1. From these locations it was possible to develop mode shape plots for the valve/bookend configuration. For the swept sinusoidal and broadband random structural identification tests, typically the response at only one location was measured. This allowed for checking the natural frequencies but not the mode shapes.

Two strain gages were mounted on the yoke of the valve. One mounted on the face would respond to axial loads and bending about the Y-axis (along the pipe axis). The second was mounted on the edge and measured strain produced by axial loads and bending about the X-axis (perpendicular to the pipe axis). Strains were measured and recorded

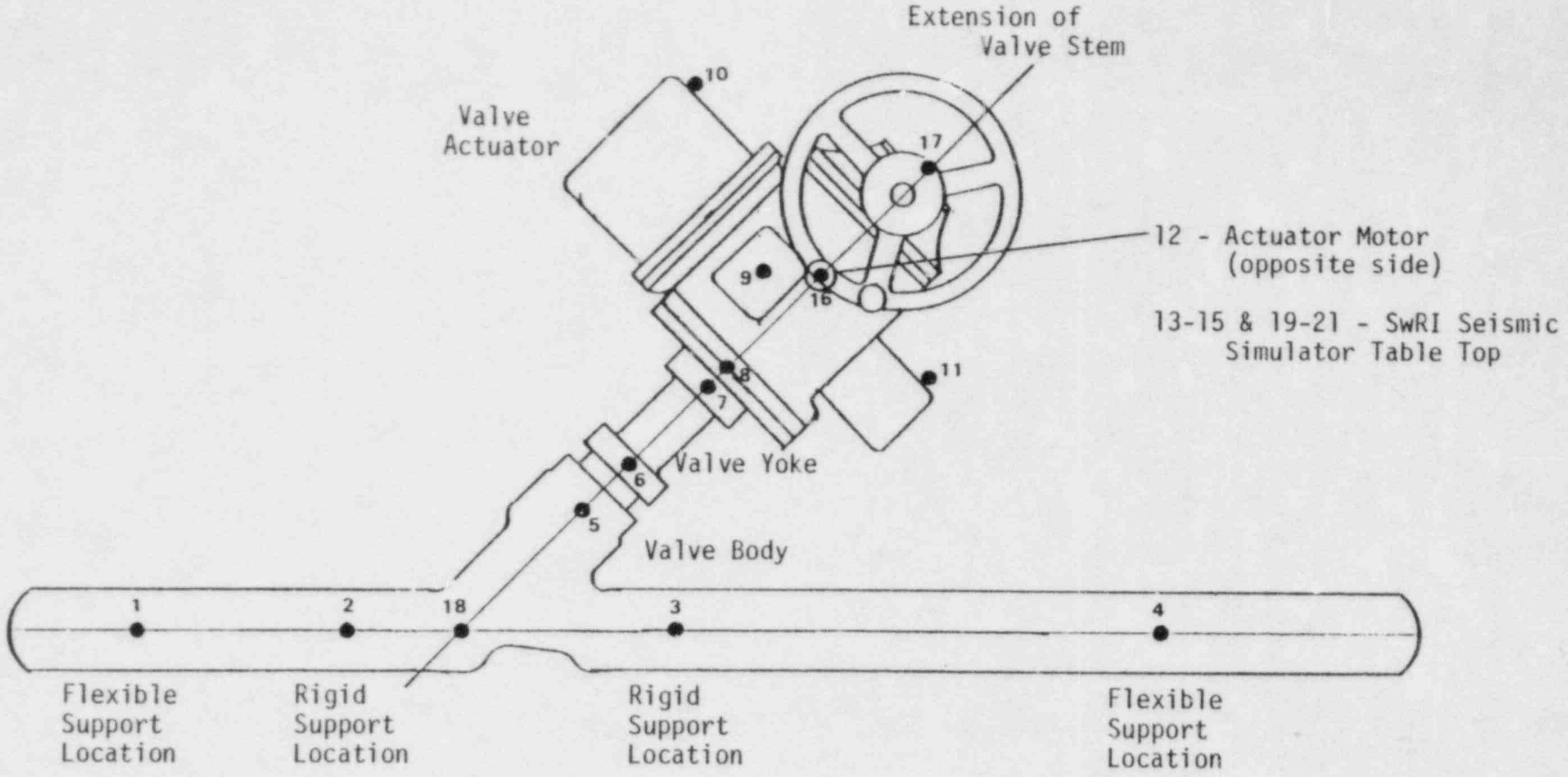


Figure 3.3-1 Location of Instrumentation

during the seismic qualification tests as one indication of functionality.

The functional state of the valve was also monitored by the continuity across the limit switches in the actuator. These were recorded on a strip-chart recorder so that any change in state could be noted. In addition the presure applied to the upstream side of the valve was monitored as an indication of leakage.

As was noted earlier, the intention of the tests performed was to look at a variety of methods appliable to seismic qualification of line mounted equipment. It was not the intent of the program to perform a qualification test. Because of this, the instrumentation was primarily used to monitor the response characteristics of the valve, with minor emphasis on the functional characteristics.

4.0 TESTING

4.1 Structural Identification

The tests performed on the valve can be divided into two separate categories, structural identification and multifrequency excitation, and are summarized in Table 4-1. A number of different procedures were used to determine the natural frequencies, mode shapes, and damping of the valve assembly in a number of configurations. Included were swept sine, broadband random, and impact hammer tests at a number of excitation levels. The intent was to look at the various procedures typically used for structural identification, and obtain some indication of potential sources of error in the results. The second group of tests, multifrequency excitation, included several methods that can be used to seismically qualify line mounted equipment.

In most seismic qualification programs some attempt is made to identify the important dynamic characteristics of the valve assembly including natural frequencies, mode shapes, and damping. Although this is not required for qualification, the information is useful for subsequent analysis of the test data and analytical models of the item. Normal resonance search tests have often been performed using swept sinusoidal excitation at a low input level (i.e., 0.2 g's peak). In this program, a number of tests were performed to look at possible variations and problems that may be encountered in using this type of test to predict response due to high level random excitation. Figure 4.1-1 shows typical results for two levels of excitation and how the frequency, 24.2 to 23.2 Hz, and amplification, 12.2 to 9.3, decrease with increasing excitation amplitude. If the shift in frequency is significant problems may arise, while the higher indicated amplification will tend to produce conservative results.

A second concern with swept sine testing is the influence of table/test item interaction. With the table tied down at the corners the indicated natural frequency and amplification are increased. In this condition one obtains a better indication of the valve resonance while the table centered results should be used in attempts to analytically match biaxial test results. The influence of the valve mounting configuration is shown in Figure 4.1-2. The first natural frequency has

TABLE 4-1
SUMMARY OF TESTS ON LINE MOUNTED VALVE

I. Structural Identification

  A. Rigid and Flexible Mounting of Valve

    1. Table Fixed at Corners
      a. Sine Sweep (0.1, 0.2 and 0.4 g peak, 1-60 Hz)
      b. Random Excitation (0.05, 0.2, 0.4, 0.5 g rms, 3.5 minutes)
      c. Impact Hammer (3 lb hammer with three samples)
    2. Table Free
      a. Sine Sweep (0.05, 0.1, 0.2, 0.4 g peak, 1-60 Hz)
      b. Random Excitation (0.2, 0.4, 0.8 g rms, 3.5 minutes)
      c. Impact Hammer (3 lb hammer with three samples)

II. Multifrequency Excitation

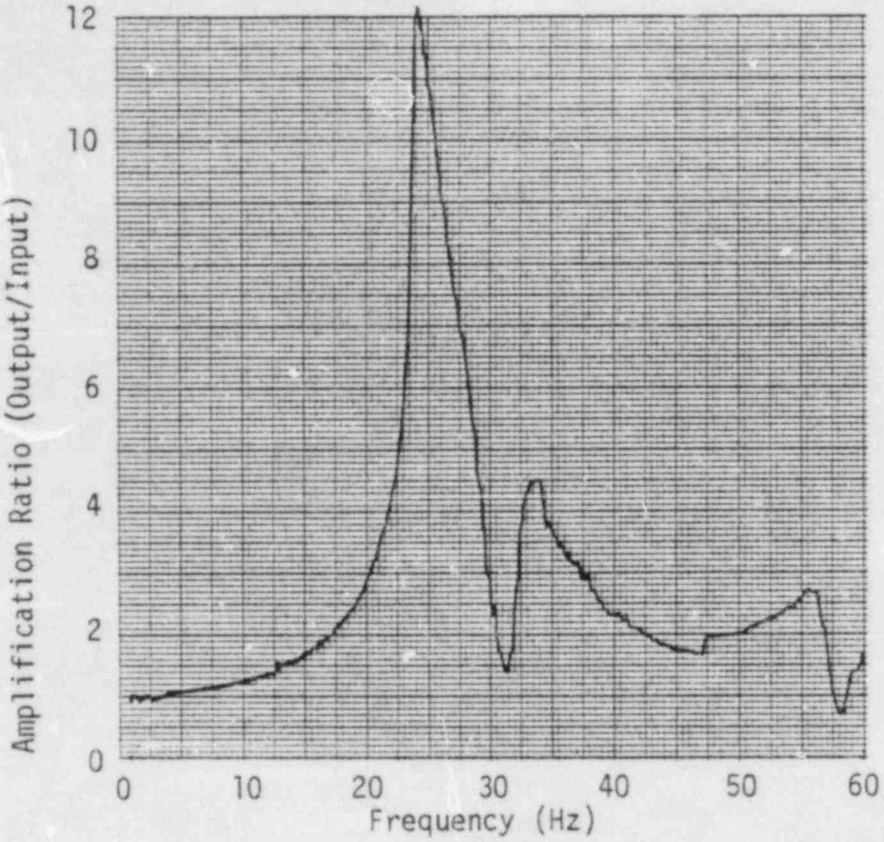
  A. Rigid Mounting of Valve

    1. R.G. 1.60 (1 g ZPA)
    2. Broadband Random (1-50 Hz, flat at 2.5 g)
    3. Sine Beats (pauses of 1.0 x beat period 2, 5, 10, 20, 31.5 Hz)
    4. Swept Narrowband Random (5 to 50 Hz, 2 Hz bandwidth)

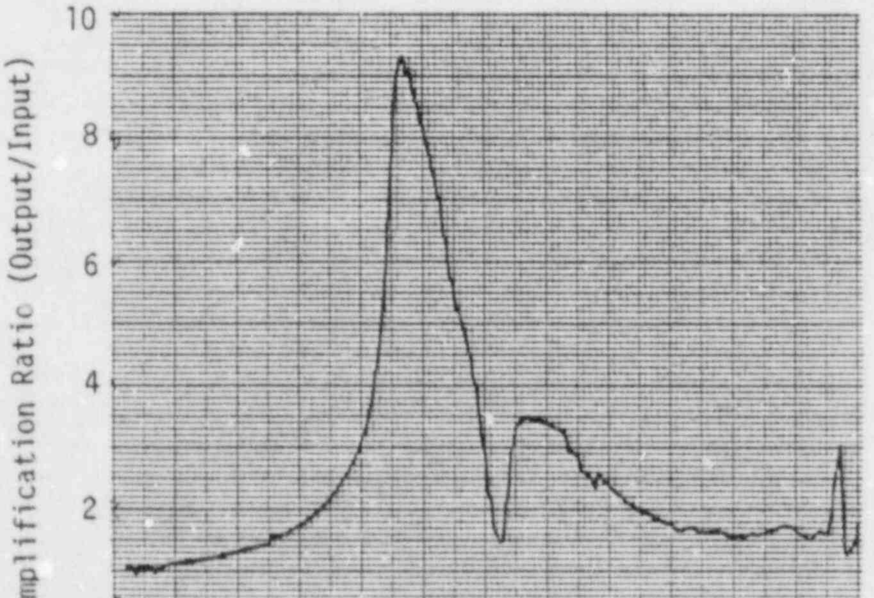
  B. Flexible Mounting of Valve

    1. R.G. 1.60 (1 g ZPA)
    2. Broadband Random (1-50 Hz, flat at 2.5 g)

Valve Closed and Pressurized to 1000 psig for Most Testing.

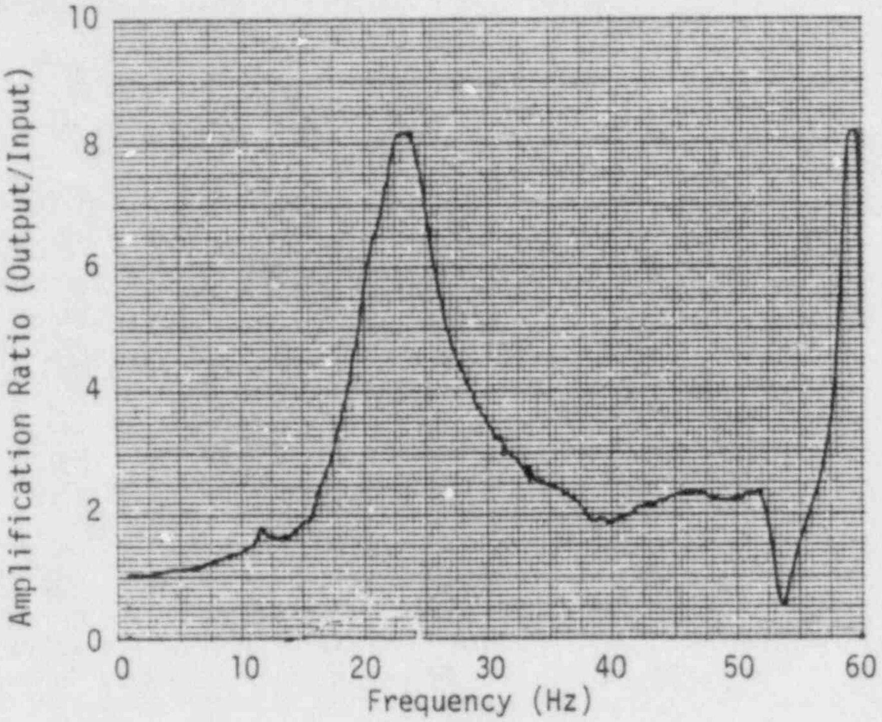


a) 0.2 g's peak input

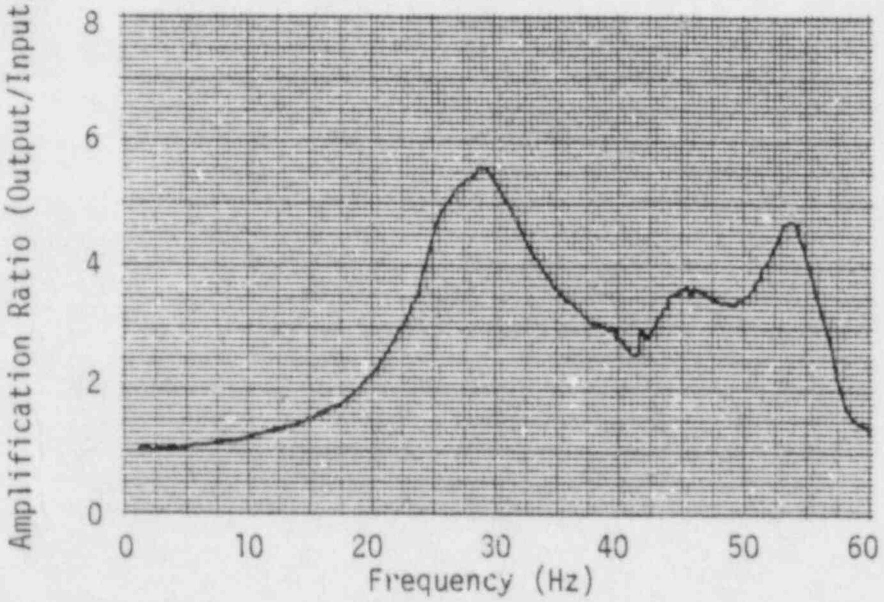


b) 0.4 g's peak input

Figure 4.1-1 Amplitude Influence on Swept Sine Resonance Searches, Y-Input, Y-Response at Actuator Motor, Flexible Supports



a) Flexible Mount



b) Rigid Mount

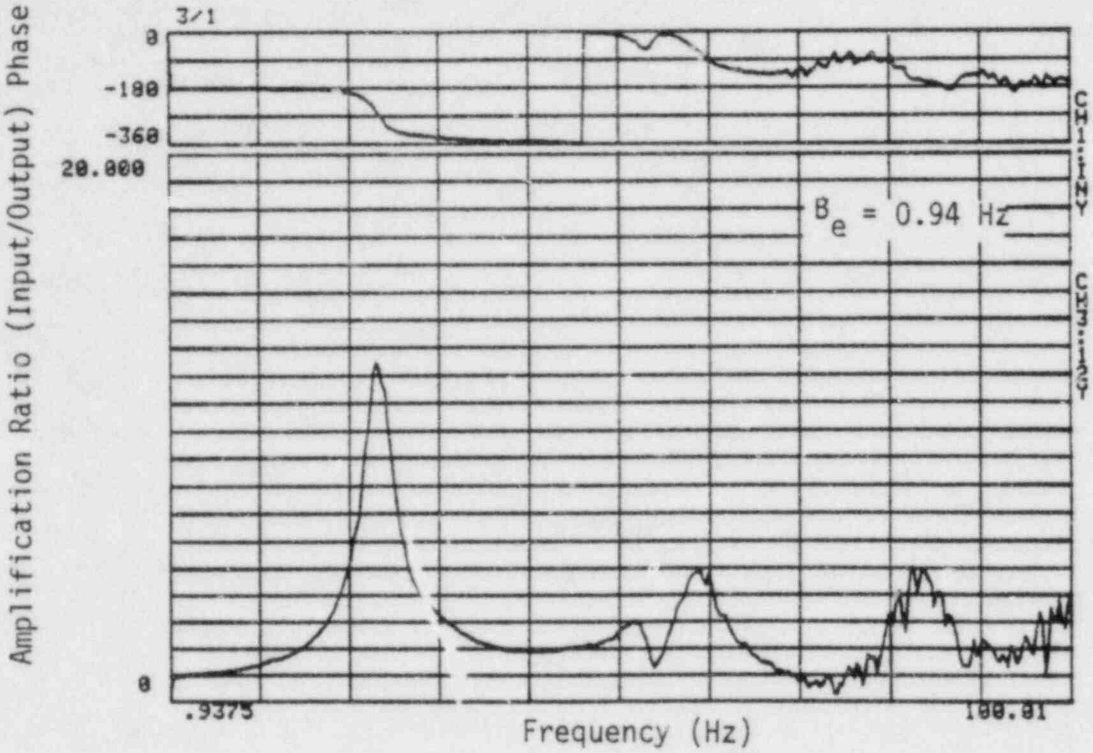
Figure 4.1-2 Mounting Configuration Influence on Swept Sine Resonance Searches, Y-Input, Y-Response at Actuator Motor, Table Centered a lower frequency and higher amplification for the flexible mount when compared to the rigid mount. These results demonstrate how a typical valve will couple with the supporting piping system.

Broadband random (1 to 40 Hz) excitation was also used to determine transfer functions using a ZONIC modal analysis system. In most instances the random and swept sine testing results are similar. The effects of valve mounting, table position, and input levels were again noted. Figure 4.1-3 shows a sample of the cross coupling between Y, horizontal, and Z, vertical, response at the actuator motor.

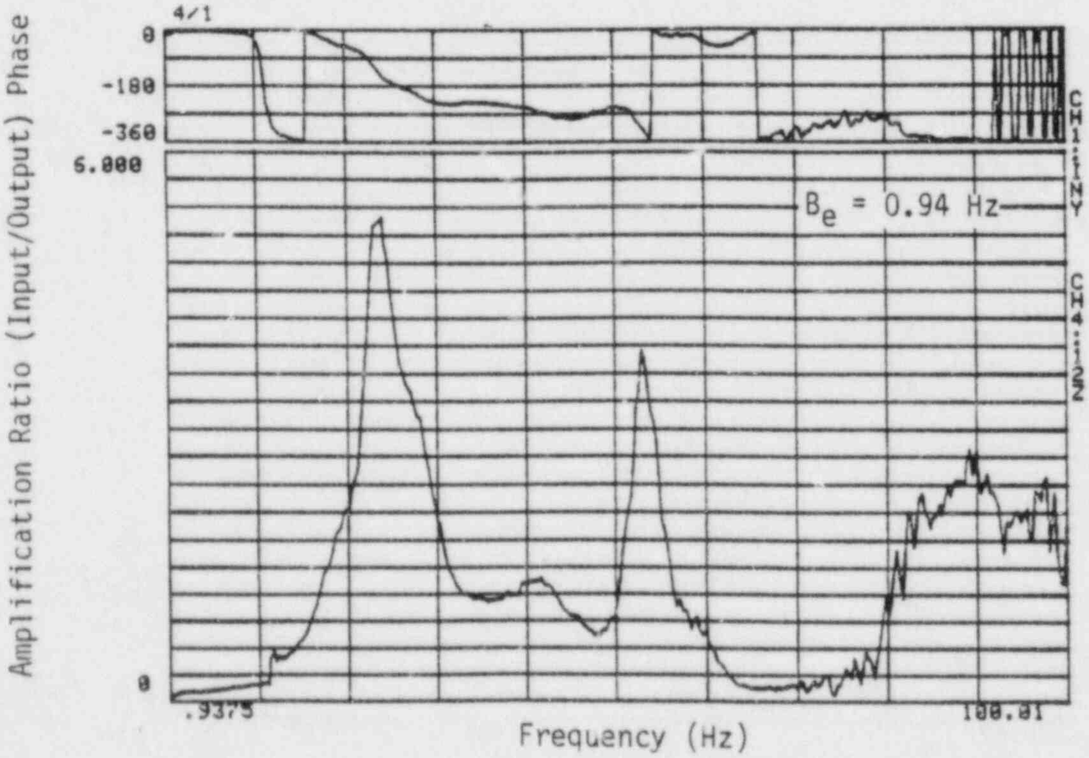
The ZONIC system was also used to develop mode shapes using an impact hammer and measuring the response at twenty-one locations on the valve and table. Excitation was at the actuator motor, and triaxial response was measured at specified locations. There are noticeable differences between natural frequencies obtained for the impact hammer tests and the swept sine and random tests. The primary source of these discrepancies seems to be the level of excitation associated with the hammer testing. It is felt that there was insufficient energy to excite all the modes. In addition there is some influence due to the difference between base excitation for sine and random testing, and elevated excitation for hammer testing. Figure 4.1-4 is a sample of the mode shape results obtained using the impact hammer.

Table 4-2 summarizes some of the data for the structural identification testing. The results presented are for swept sine test at 0.2 g's input, broadband random input at 0.2 g rms input, and the three pound impact hammer. Results are for both rigid and flexible valve supports and with the vertical table fixed and free. The following observations can be made:

1) Fixed table natural frequencies are higher than the free table results. There is some test item/table interaction.
2) Impact testing results are not affected significantly by the table configuration. Some form of nonlinearity influences the response, and the excitation level is probably not sufficient to produce any interaction.
3) Sine and random testing show similar natural frequencies.

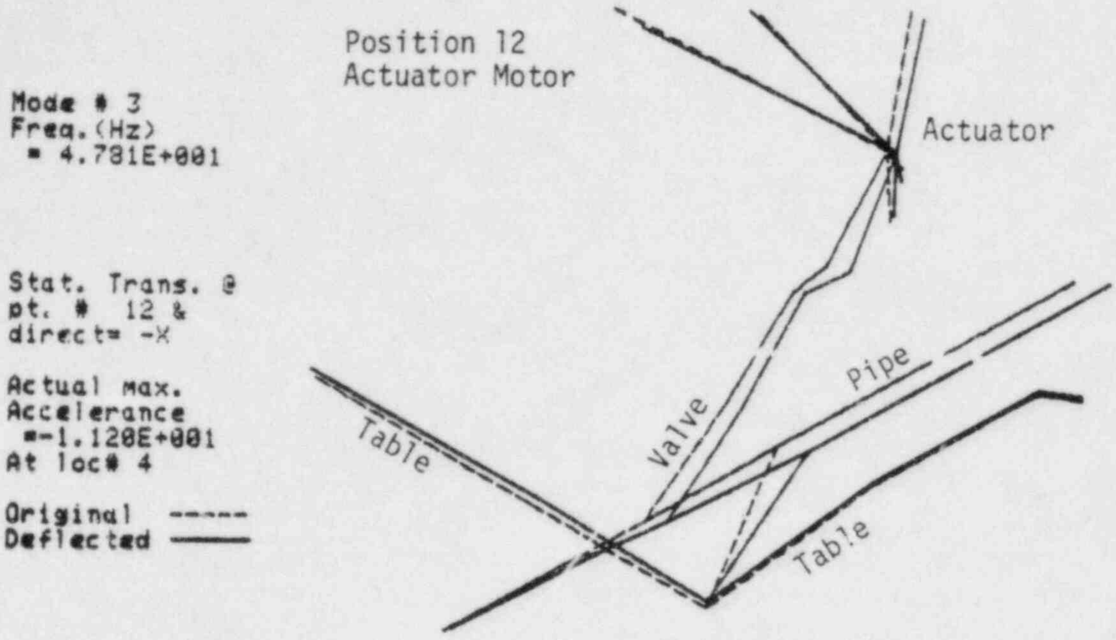


a) Y Response at Actuator Motor

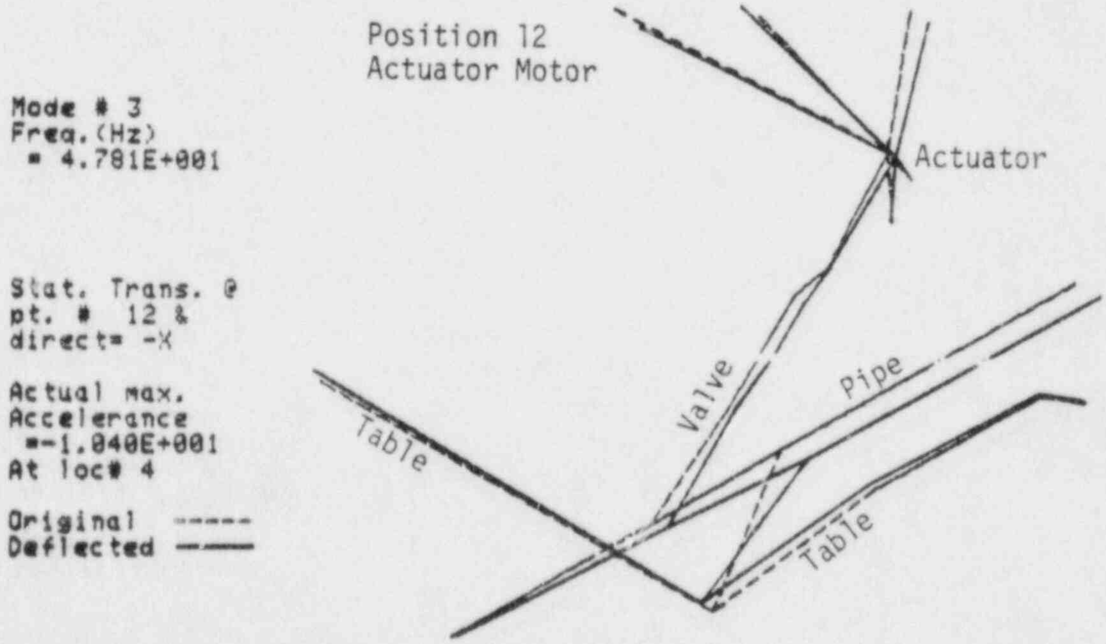


b) Z Response at Actuator Motor

Figure 4.1-3 Cross-Coupling as Demonstrated During Broadband Random Excitation at 0.2 g rms in Y-Direction



a) Flexible Mounts Table Fixed



b) Flexible Mounts Table Free

Figure 4.1-4 Mode Shapes Obtained Using Impact Hammer

TABLE 4-2
SUMMARY OF STRUCTURAL IDENTIFICATION TESTING

Mounting Axis	Valve Support Configuration	Table Configuration	Excitation Direction	Excitation Type	Response Direction	Resonance Frequencies			
X-Z	Rigid	Fixed	X	Sine	X	----	35.5	----	
			Y	Impact	All	13.4	35.0	45.9	
		Free	X	Sine	X	----	29.7	----	
			X	Impact	All	----	----	44.1	
			Y	Impact	All	13.4	23.8	46.5	
			Z	Sine	Z	----	----	44.0/ 48.2	
					Y	----	----	47.9	
	Flexible	Fixed	X	Impact	All	11.2	24.7	47.8	
		Free	X	Impact	All	11.2	----	47.8	3.8*
Y-Z	Rigid	Fixed	Y	Sine	Y	----	37.0	----	
			Y	Random	All	31.3	37.8	----	
			Y	Impact	All	26.5	44.7	----	
			X	Impact	All	26.9	40.9	47.5	
		Free	Y	Sine	X	12.8	42.5	----	
					Y	29.0	45.5	53.3	
					Z	----	42.5	54.2	
			Z	Sine	Z	----	----	51.5	
					Y	----	----	52.8	
	Flexible	Fixed	Y	Sine	Y	----	24.2	34.2	55.7
					Z	----	26	32.0	56.5
			Y	Random	All	12.2	23.7	----	53.4
			Y	Impact	All	12.5	----	32.5	3.4*
		Free	Y	Sine	Y	----	23.5	----	59.3
					Z	12.5	17.0	23.0	53.5
			Y	Random	All	11.1	15.6	22.3	37.9
				Impact	All	12.8	----	30.3	3.4*

*These are side-to-side response characteristics of the seismic table.

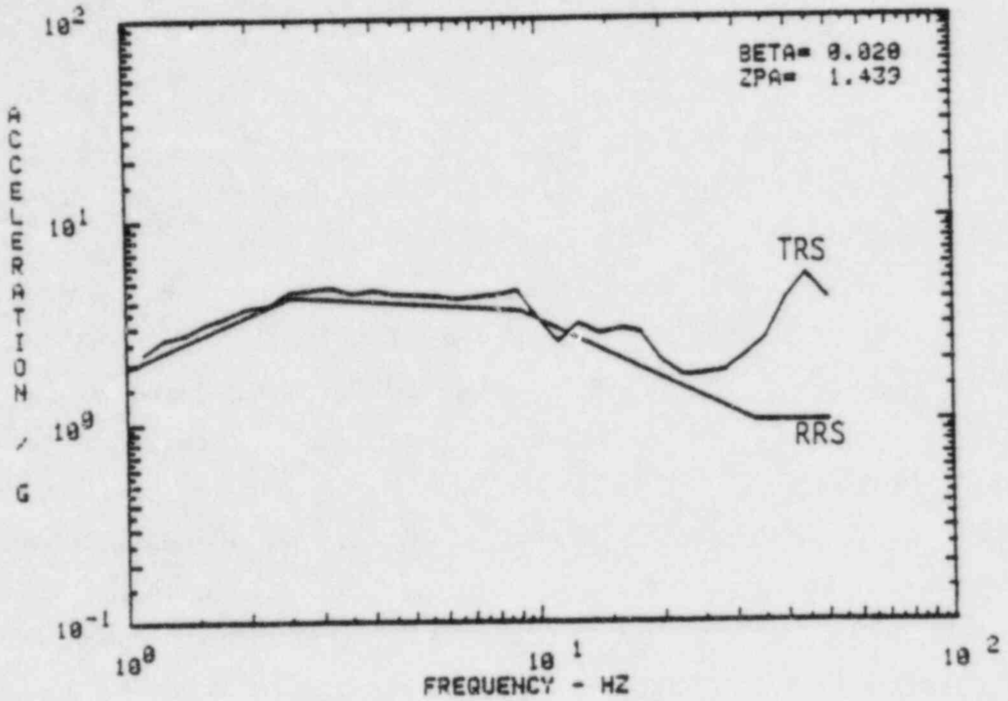
4) The first bending mode of the valve assembly is lower for the flexible supports compared to the rigid support, as would be expected.

4.2 Multifrequency Excitation

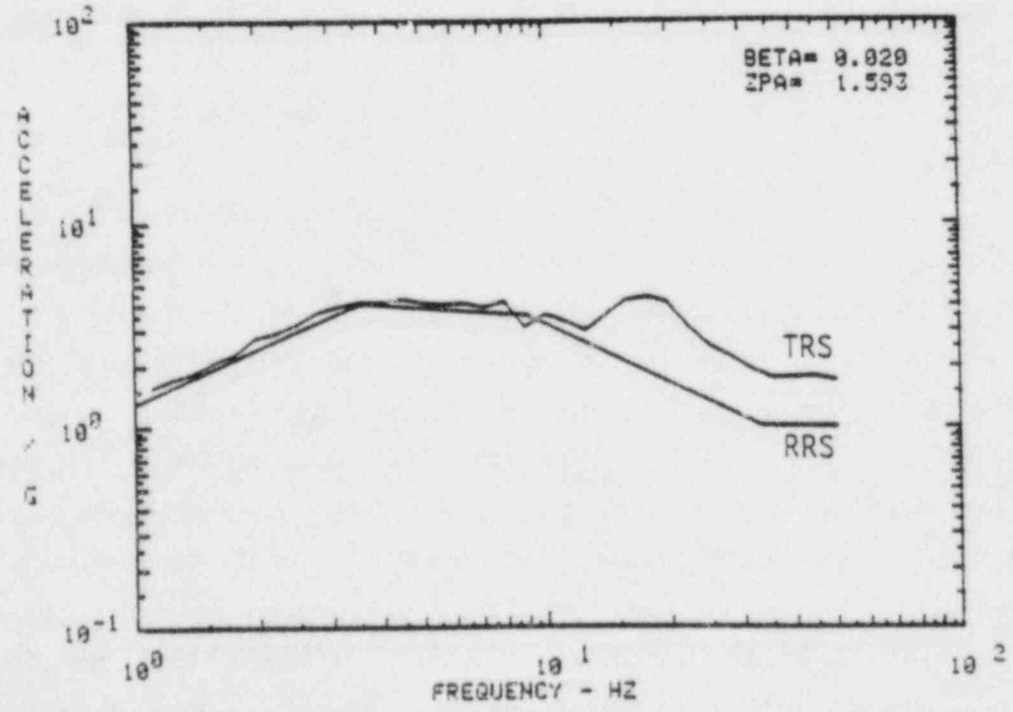
The valve assembly was also subjected to a number of different multifrequency excitations which can be be used for seismic qualification. One was a R.G. 1.60 earthquake with a ZPA of 1.0 g, and two percent damping (i.e., Figure 4.2-1). A close enveloping of the Test Response Spectrum (TRS) with the Required Response Spectrum (RRS) was obtained, except at higher frequencies. A number of tests were run with this input including valve closed, valve open, valve cycled, horizontal input only, vertical input only, and combined horizontal and vertical input. The valve functioned properly under all conditions and there was no significant difference in the input response spectra. At the elevated locations the combined loading produced more response than the uniaxial loading due to the cross-coupling of horizontal and vertical responses. This would indicate that biaxial random testing may have advantages over uniaxial testing for coupled structures.

A similar series of tests were performed for a flat random signal, as shown in Figure 4.2-2. The level was adjusted until the ZPA levels compared to the R.G. 1.60 results. The flat input type tests are similar to those reported by Kennedy [11] for fragility testing. Results were similar to those obtained from the R.G. 1.60 testing and no additional conclusions were drawn.

Sine beat tests were performed with 10 cycles/beat and a pause time equal to the excitation time. This resulted in a complete decay of the valve response prior to beginning the next excitation beat. Tests were run at both resonance and non-resonance frequencies. For the non-resonance frequencies, response followed the input almost directly, as shown in Figure 4.2-3. (Note that the data in these two plots is not time correlated.) A skewed response with acceleration higher in one direction than the other was noted for most test runs. To limit potential damage to the test item, the response at the actuator motor was limited to approximately 2 g's. This was done by adjusting the input levels until this response was obtained. As a result only minor

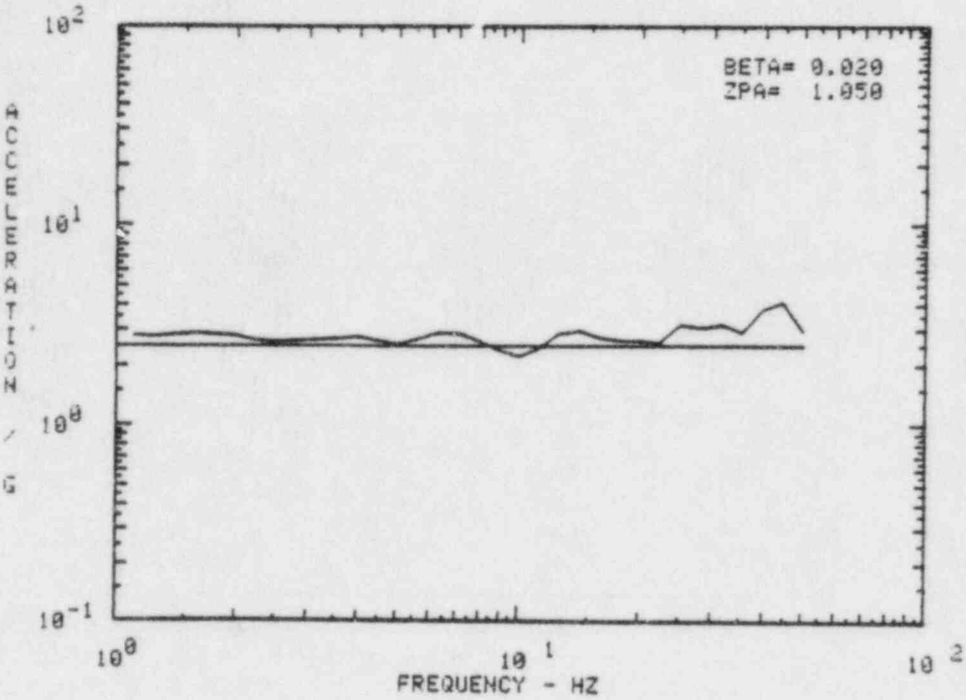


a) Horizontal

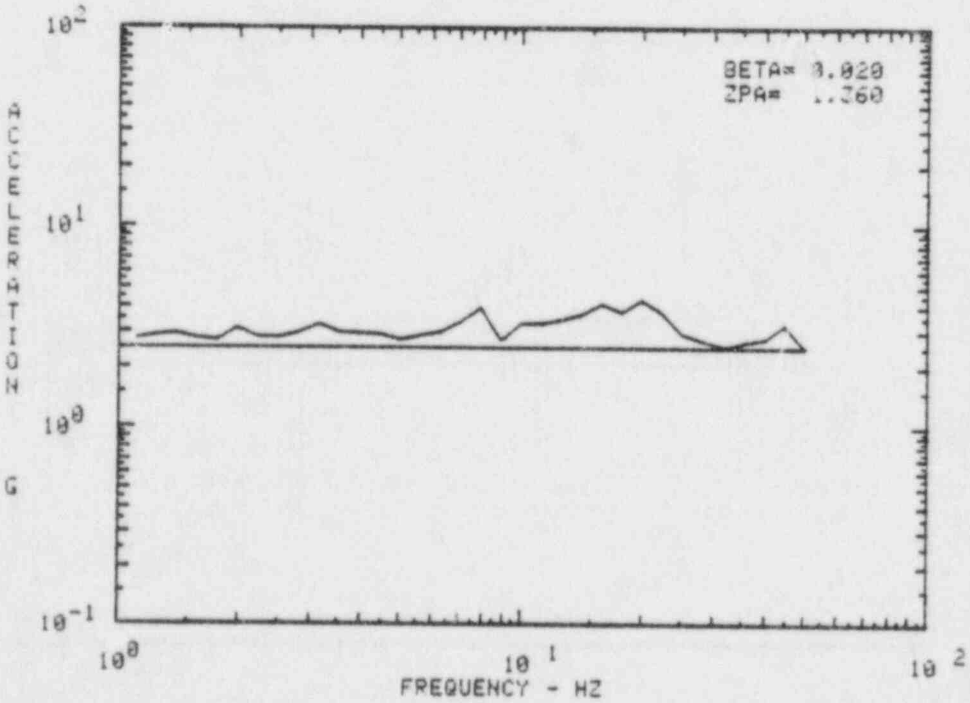


b) Vertical

Figure 4.2-1 R.G. 1.60 Earthquake Excitation Response Spectra

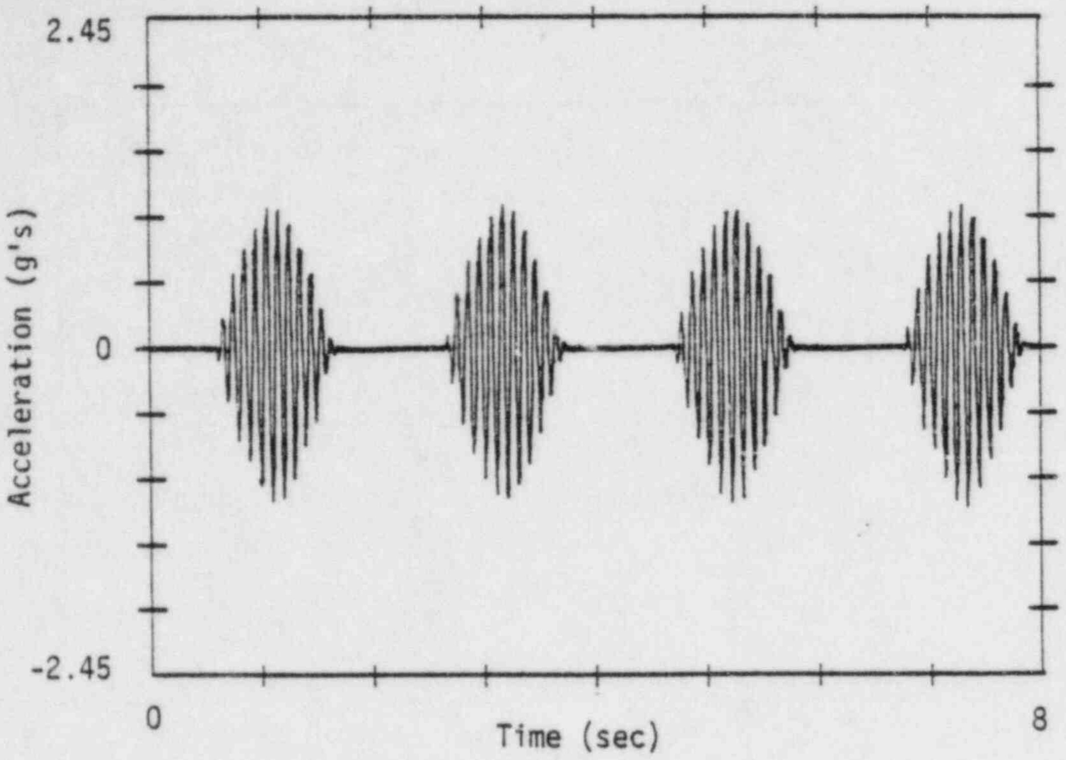


a) Horizontal

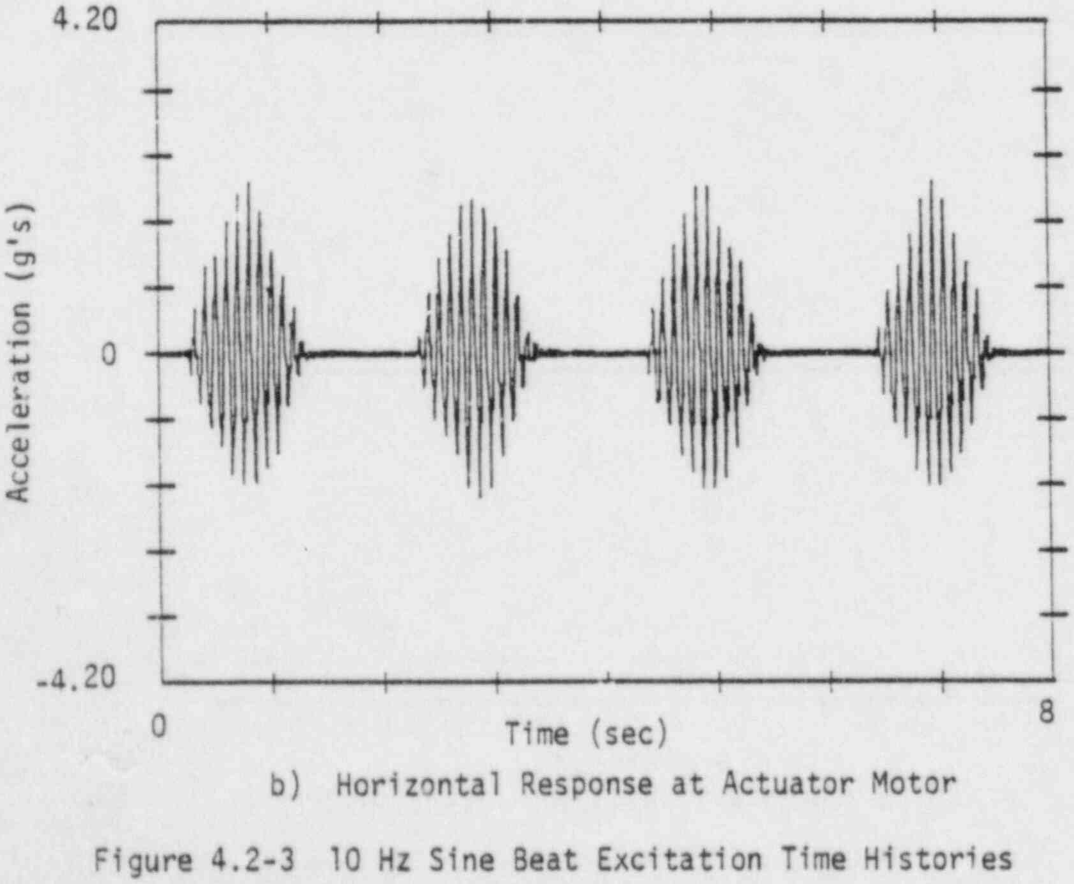


b) Vertical

Figure 4.2-2 Flat Random Excitation Response Spectra



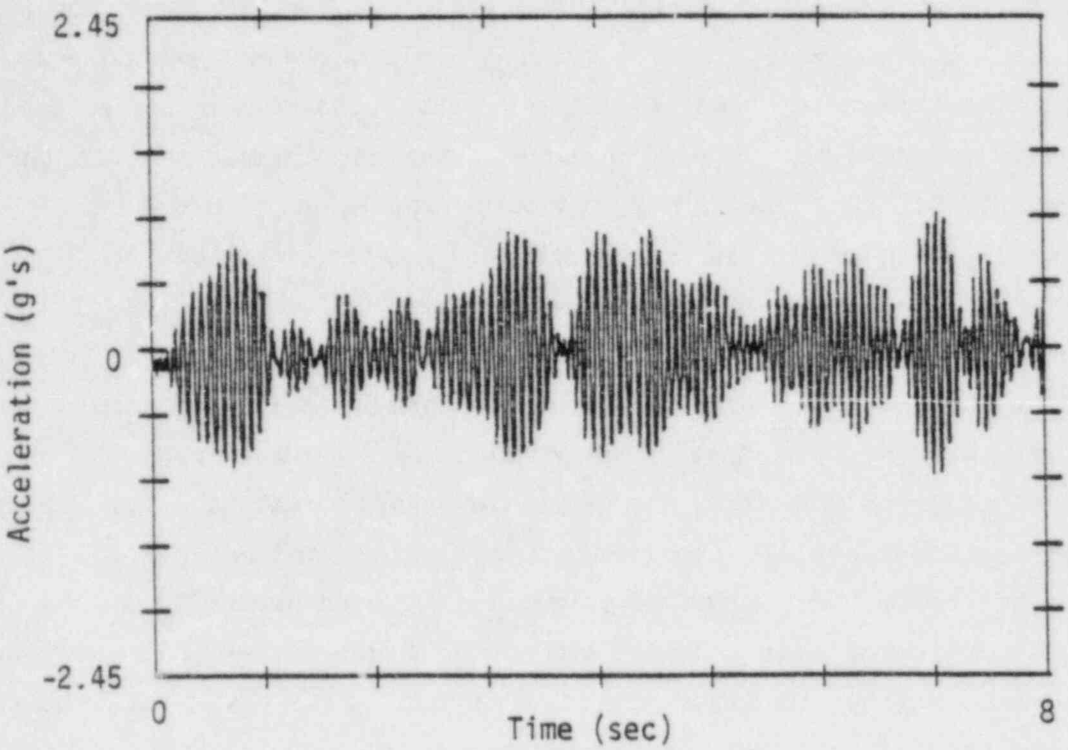
a) Horizontal Input



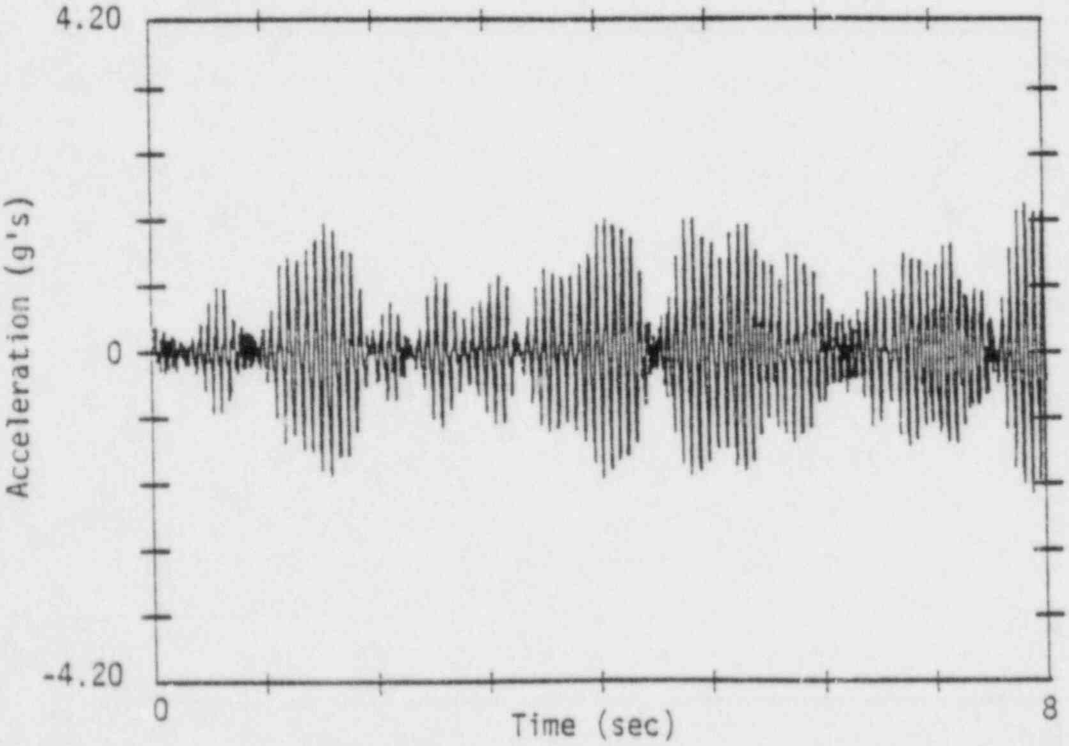
b) Horizontal Response at Actuator Motor

Figure 4.2-3 10 Hz Sine Beat Excitation Time Histories decay times were noted at resonance frequencies due to the low level of input. At the test level the induced damping due to test item/table interaction tended to dominate the response. At a higher input level, typical of most qualification testing, this would not be the case.

The final set of multifrequency tests consisted of swept narrowband random excitation. A random noise generator signal was fed through a tracking filter whose center frequency was swept from 5 to 50 Hz at one octave per minute. The bandwidth of the filter was set at 2 Hz. Both peak and rms levels of input acceleration were used to control the input level. Due to problems associated with the feedback loop of an automatic control system, manual control was maintained on peak accelerations. The time history was observed on a scope and the input level adjusted such that the peaks were kept constant. For RMS control the instantaneous RMS acceleration was determined using a FFT analyzer, and the input level adjusted to maintain a constant RMS. A time history of a portion of such a test is shown in Figure 4.2-4. The response was found to follow the input almost directly. (Note again that the data in these two plots is not time correlated.)



a) Horizontal Input



b) Horizontal Response at Actuator Motor

Figure 4.2-4 Swept Narrowband Random Excitation Time Histories

5.0 DISCUSSION AND CONCLUSIONS

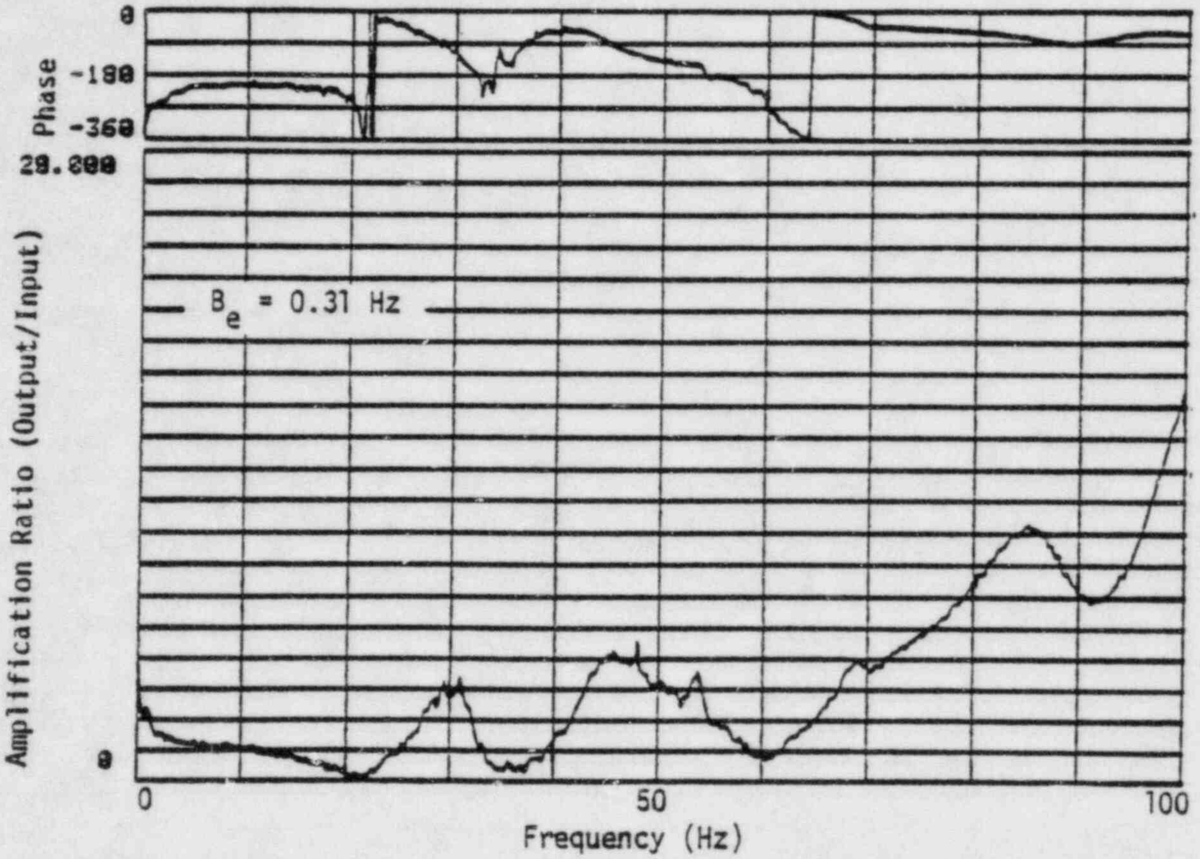
5.1 Structural Identification Procedures

In this program three different types of structural identification tests were performed, swept sine, broadband random, and impact hammer. Historically swept sinusoidal tests have been the predominate method used for structural identification. Tests are normally run at a low excitation level that is significantly below the full scale seismic event. From tests performed herein (Figure 4.1-1), it can be seen that the level of excitation has an influence on both the measured natural frequency, and damping of the structure. As the level increases, the natural frequency decreases and the damping increases. The change in damping will tend to produce conservative results if subsequent analysis is performed at the full level excitation. Results of the shift in frequency are dependent on the nature of the full level response spectrum. If the shape is broadband ground level input, the results will not be influenced significantly. On the other hand, if a floor level frequency dependent response spectrum is used, the results may be questionable. The peak response may be shifted into or out of the peaks of the required response spectrum.

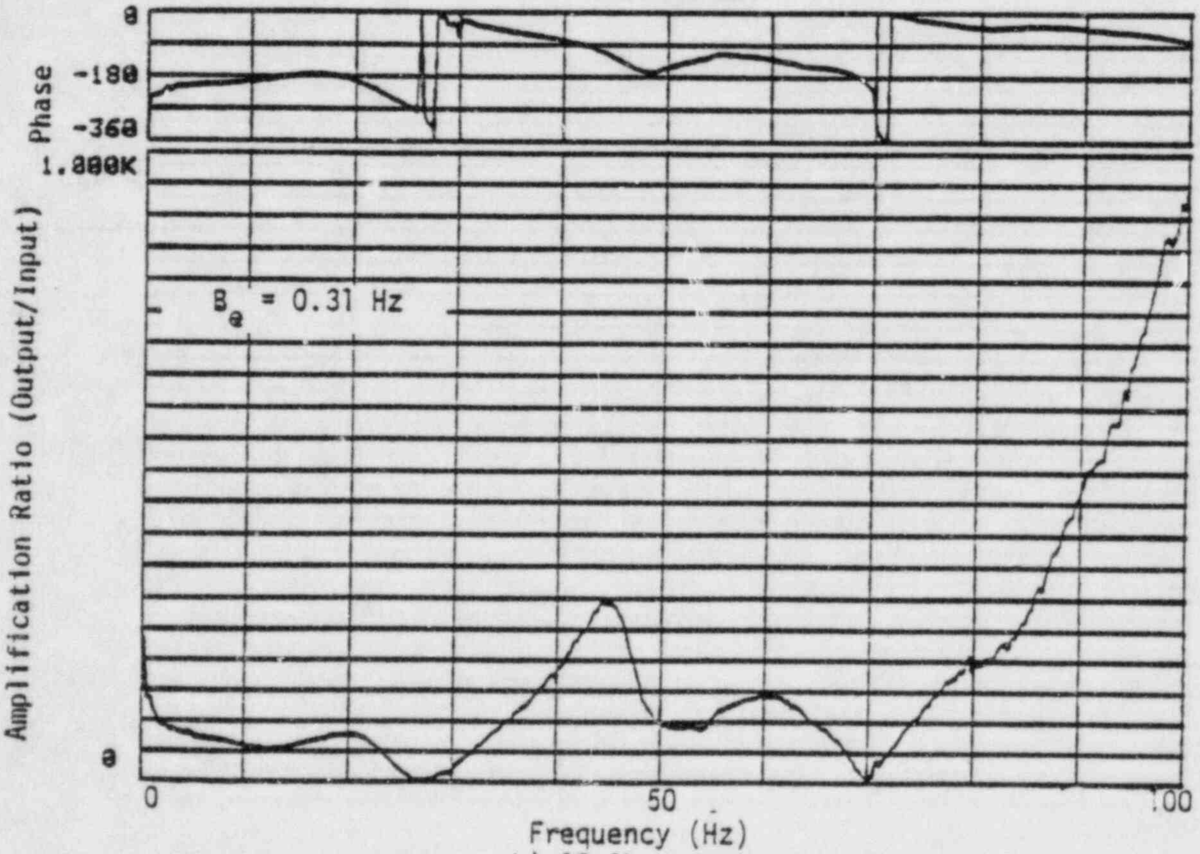
Similar results are noted for broadband random input testing. Several additional considerations need to be made for random testing in conjunction with the analysis of the data. The test time should be sufficiently long so that enough samples, 50 for this series of tests, are analyzed. This will provide some degree of statistical confidence which can be associated with the results. In addition the bandwidth of anlaysis mst be sufficiently small so that the peaks can be resolved. The required bandwidth is dependent on both the measured natural frequency and the damping of the test item. The lower the frequency and damping the smaller the bandwidth must be. There should be a minimum of three data points between the half power points of the system. Note that this was not the case for the oscillator PSD data shown in Figures 2.1-3 and 2.1-5, and therefore full amplification of the PSD was not achieved at resonance.

From the authors' experience the uses of impact hammer testing to determine the mode shapes, natural frequencies and damping requires careful attention to detail. As with the valve random tests, the number of samples (three for this case) and the analysis bandwidth (0.31 Hz) must be sufficient to accurately resolve the data. This procedure provides the best method of developing mode shape data. On the other hand, determination of the natural frequency and damping is not very straightforward. The first problem is associated with the level of input. Compared to the full scale seismic event, impact hammer testing excitation levels are normally extremely small. This has a tendency to affect both the natural frequency and damping. During the tests reported herein, three sizes of instrumented hammers were used to excite the test item. Transfer functions for each are given in Figure 5.1-1, and as can be seen are drastically different. The smallest hammer was too small to input sufficient energy into the test item to excite the bending modes. Conversely the largest hammer was so large that it was difficult to strike the item in a manner which did not influence the response. That is, the duration of the impact was too long. It was felt that the three pound hammer, Figure 5.1-1(c) was the correct size for this test item. It was sufficiently large to excite the item, but small enough to allow for a quick rebound. Of the three dynamic characteristics of the valve determined, damping was the most difficult to obtain using the impact hammer.

When performing impact tests, it is also important to look at the coherence and real and imaginary parts of the transfer function, as shown in Figure 5.1-2. They provide additional information on the validity of the transfer function. From the coherence function the frequency range where the data is useful can be determined (i.e., where the value is near 1.0). For this example only the results between 10 and 60 Hz are useful. The real and imaginary parts of the transfer function provide an indication of how well the resonances are resolved. The imaginary part should have a maximum or minimum at a resonance. Similarly, the real part should demonstrate a sharp transition from maximum to minimum or vice versa at a resonance. The results shown are not ideal. Similar results can be obtained for the phase portion of the transfer function, as shown in Figure 5.1-1(c). Rapid oscillation shows a region of questionable data. A transition through 90° or 270° should accompany the peaks of the amplification ratio.

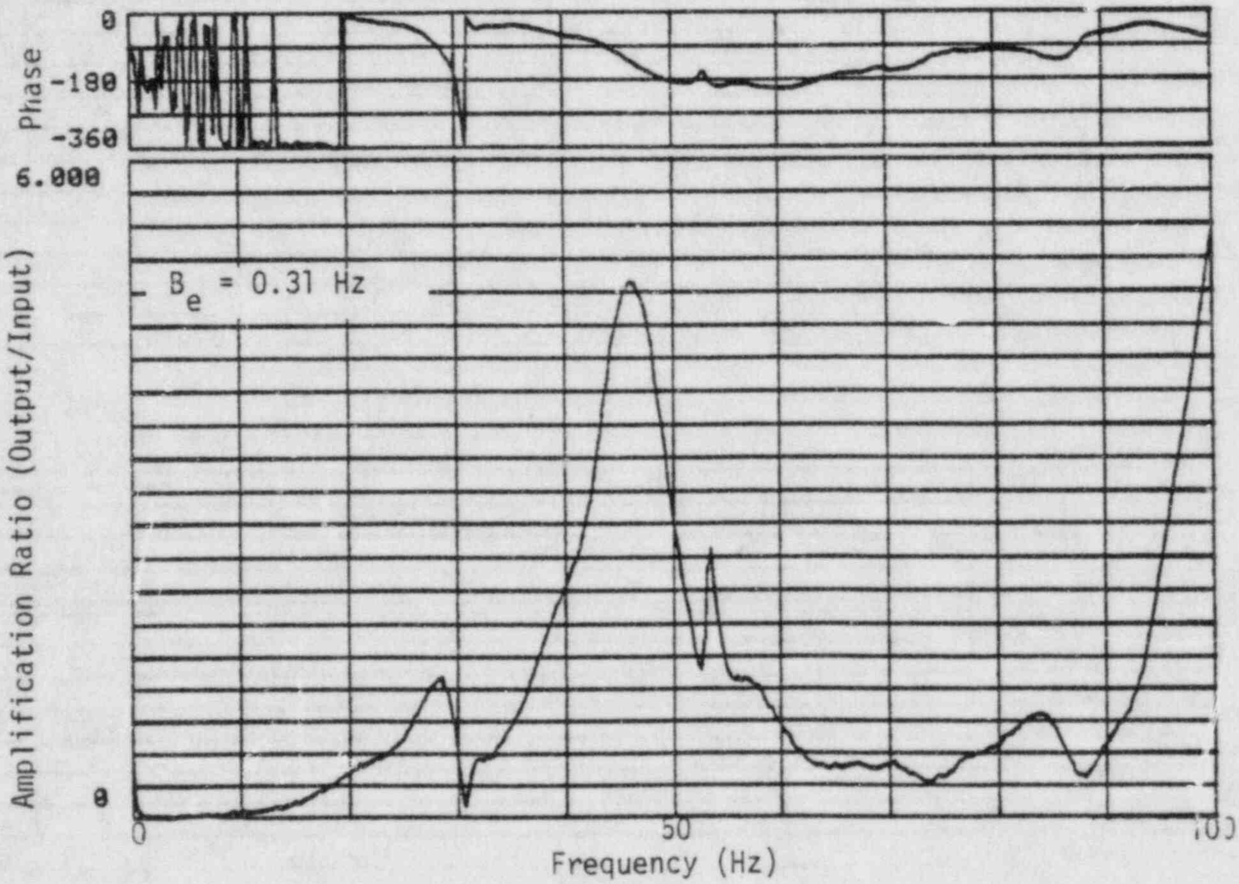


a) 1-lb Hammer



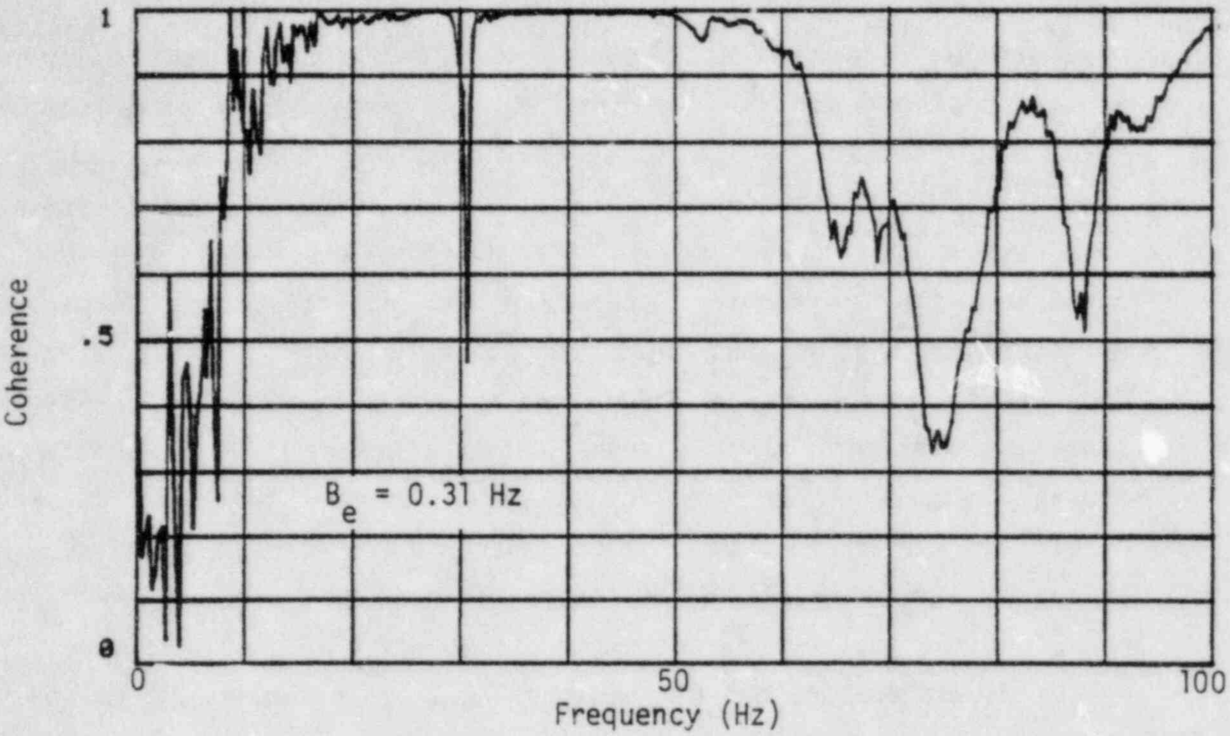
b) 12-lb Hammer

Figure 5.1-1 Influence of Impact Hammer on Structural Identification Procedure, Y-Input, Y-Response at Actuator Motor, Flexible Support, Vertical Table Fixed

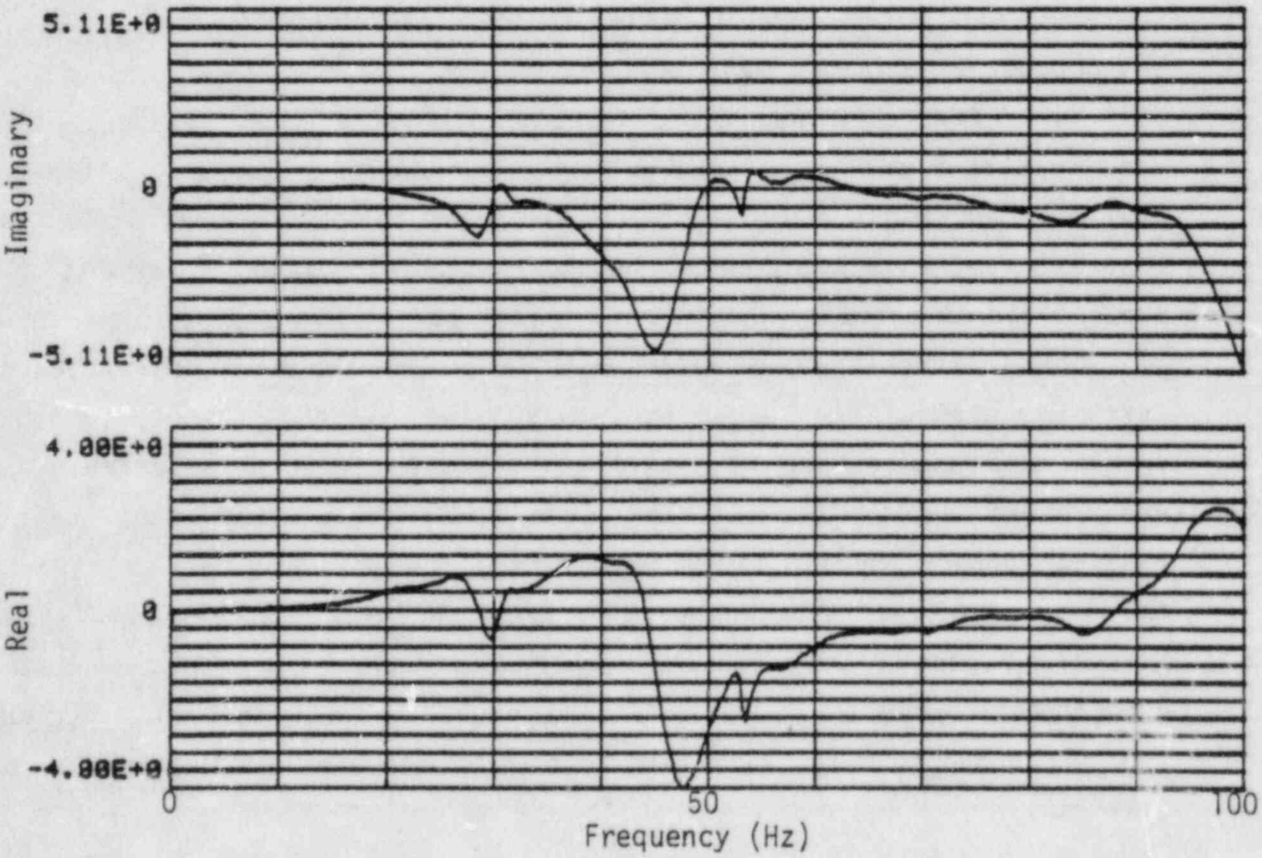


c) 3-lb Hammer

Figure 5.1-1 - Continued



a) Coherence



b) Real and Imaginary Parts of Transfer Function

Figure 5.1-2 3-lb Hammer Impact Structural Identification Data, Y-Input, Y-Response at Actuator Motor, Flexible Supports, Vertical Table Fixed

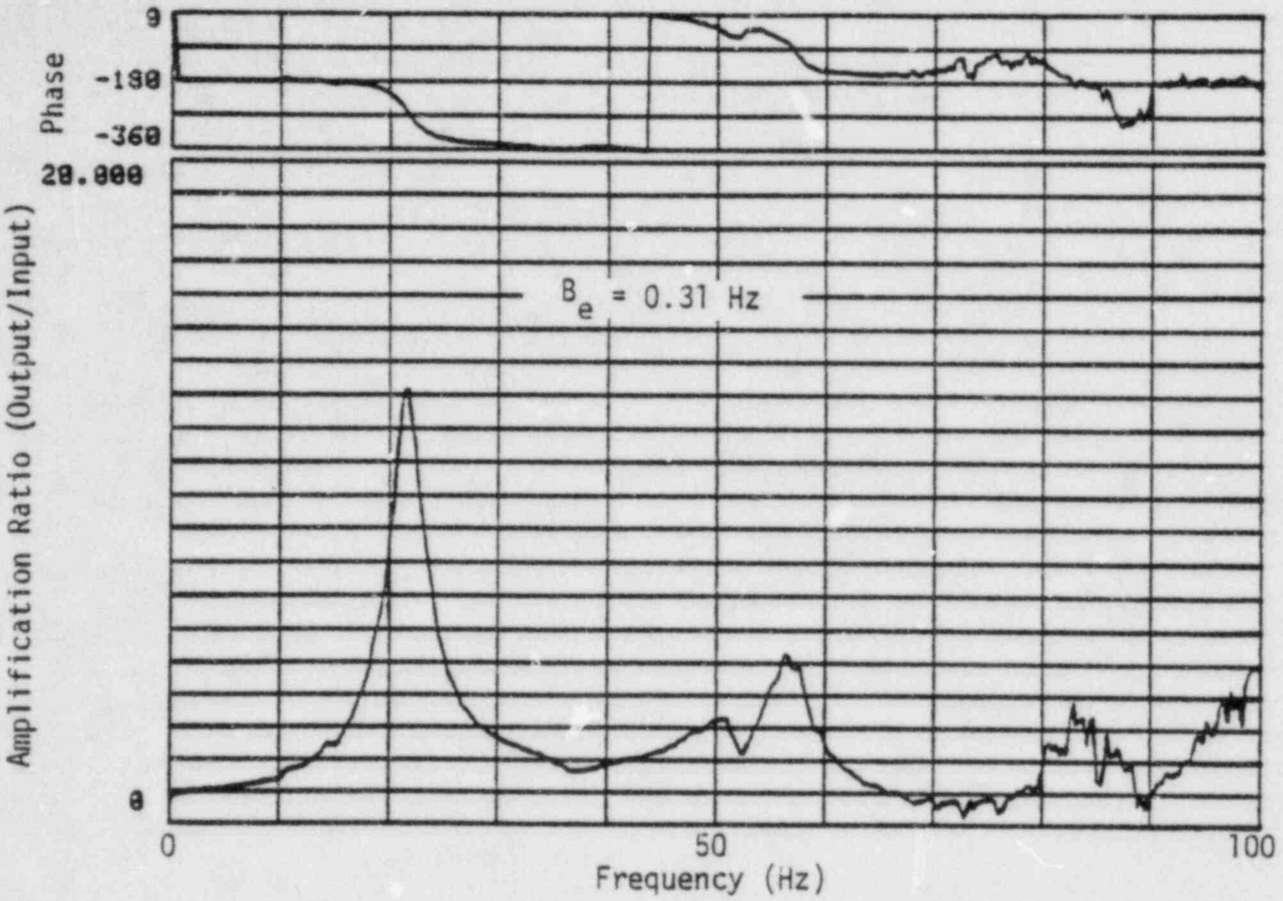
Another consideration in the performance of structural identification testing is the influence of test item/table interaction. The first question to be answered is if the tests are designed to determine the characteristics of the as-tested, or the as-installed device. In the as tested case (Figure 5.1-3), the tests should be performed with the vertical axes free and centered. This most closely approximates the seismic test condition for the biaxial simulator. Conversely, to limit the influence of the interaction, the vertical table may be restrained against motion (Figure 5.1-4). This more closely represents in-service conditions. The two test conditions result in different natural frequencies and indicated damping. Also shown are the coherence which indicates that the response is in fact a result of the input up to approximately 50 Hz.

A recent publication [12] reaches some of the same conclusions that have been drawn from this study. This document also goes into details on the various procedures for parameter estimation. However, it deals primarily with the analytical aspects of the problem, while we have dwelled on experimental problems herein.

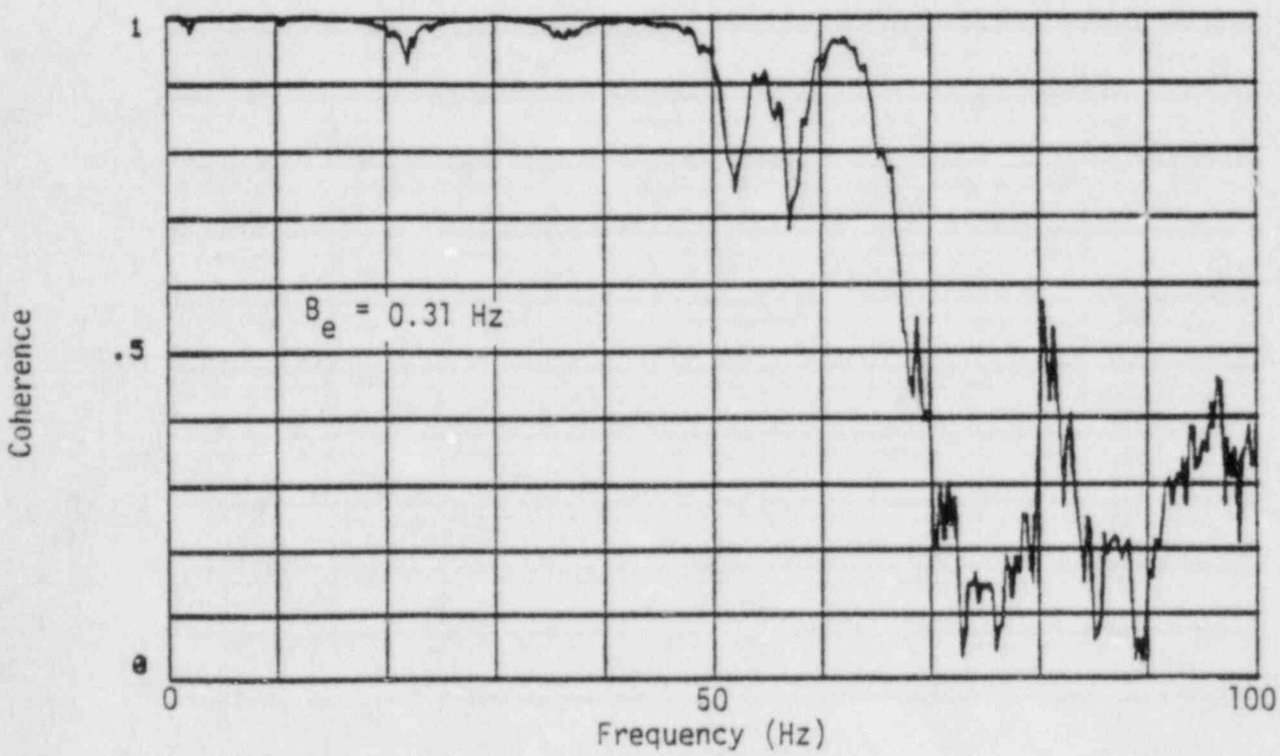
5.2 Mounting Configuration

Two different mounting configurations, "rigid" and flexible", were used to attach the valve assembly to the bookends for tests. As noted earlier, the rigid condition was designed to simulate typical test conditions of a bolted flange mounted on steel bookends. The flexible support was an attempt to simulate a valve mounted in a pipe line.

The influence of valve support on the response at the actuator level has already been shown in Figure 4.1-2. Typically the resonance search data showed that the rigid mount has a higher natural frequency and greater damping than the flexible condition. To verify that similar behavior occurs for earthquake excitation, the strong motion portion of the R.G. 1.60 earthquake run was analyzed. The acceleration time history, Figure 5.2-1; PSD, Figure 5.2-2; and transfer function and coherence, Figures 5.2-3 and 5.2-4, were used. (Note that all analysis was performed on 12 data samples with an analysis bandwidth of 0.94 Hz.)

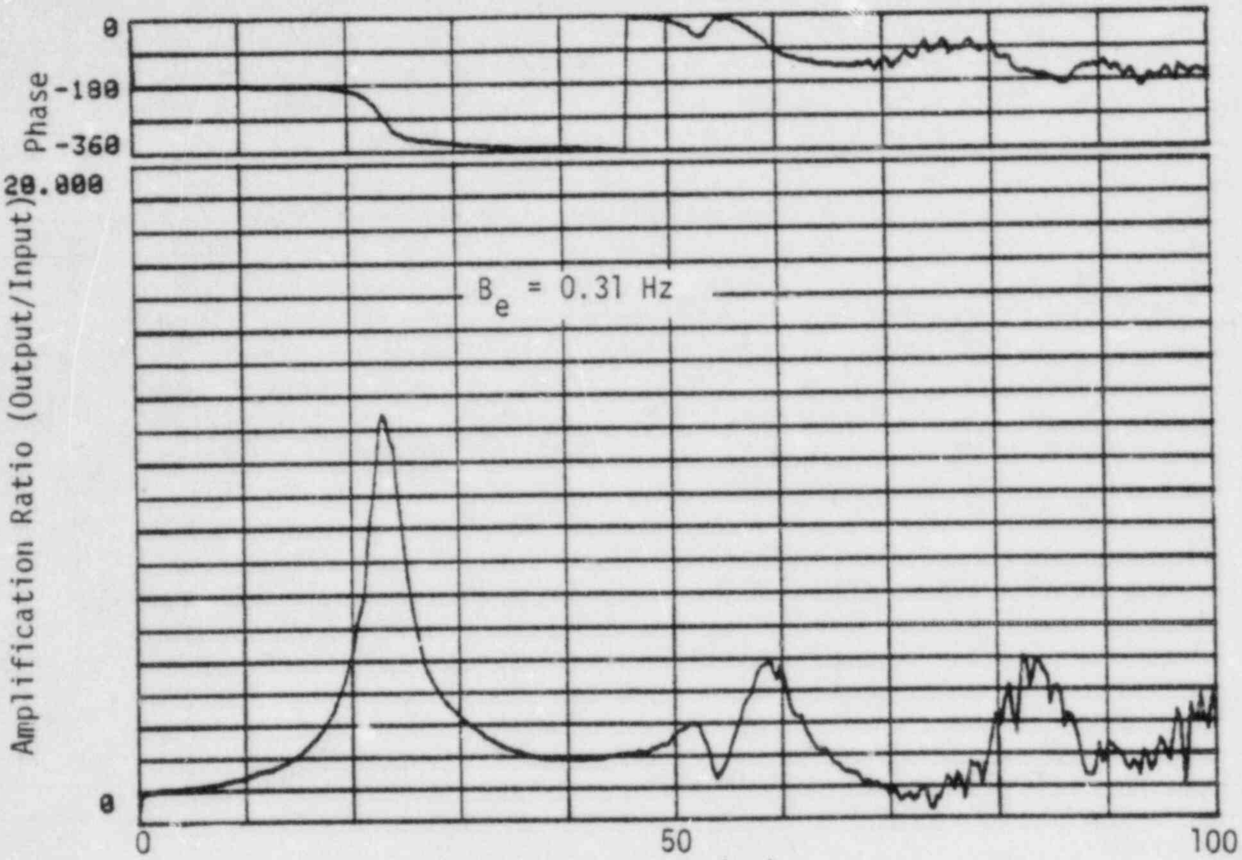


a) Transfer Function

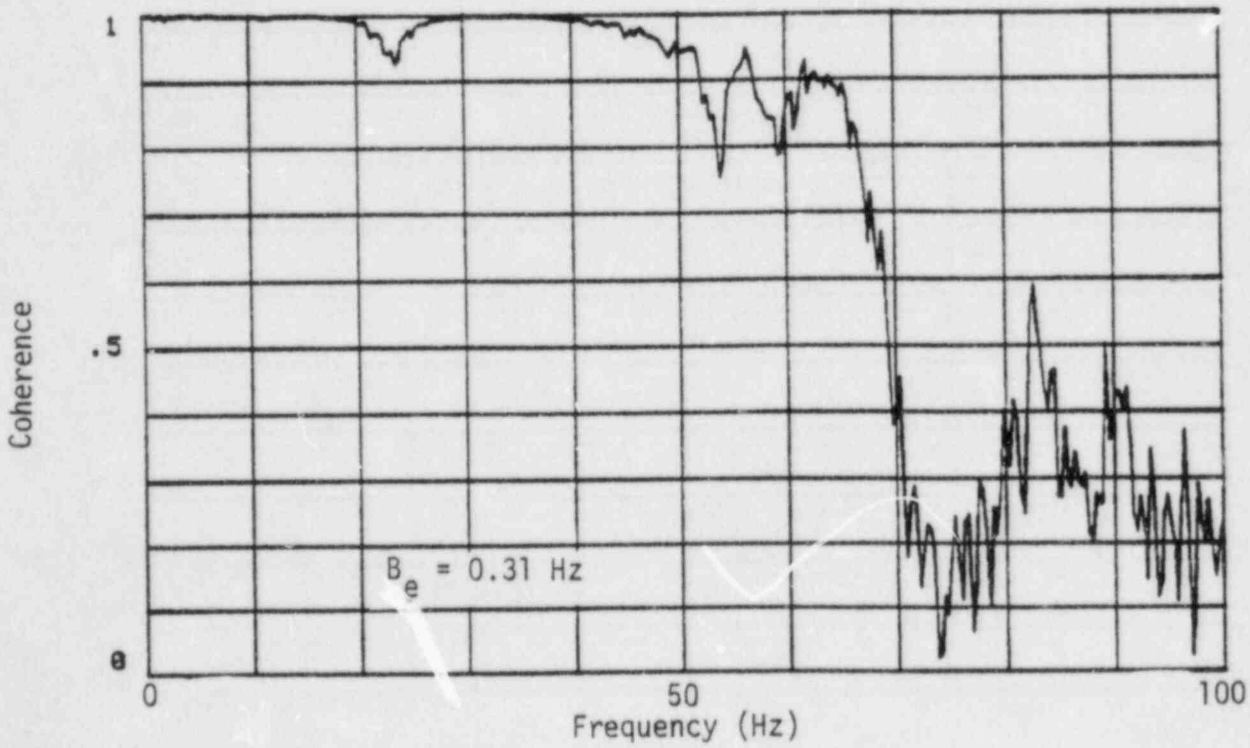


b) Coherence

Figure 5.1-3 Broadband Random Structural Identification, 0.2g rms, Y-Input, Y-Response at Actuator Motor, Flexible Supports, Vertical Table Free

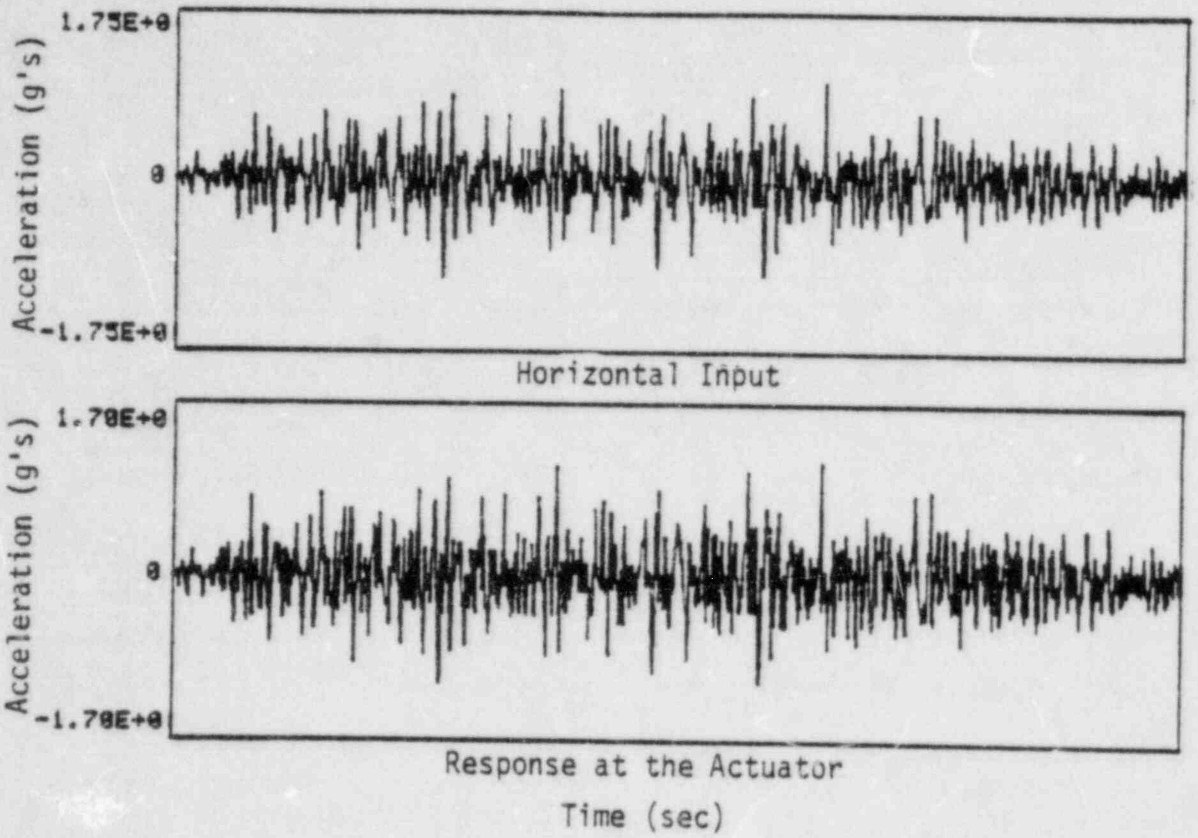


a) Transfer Function

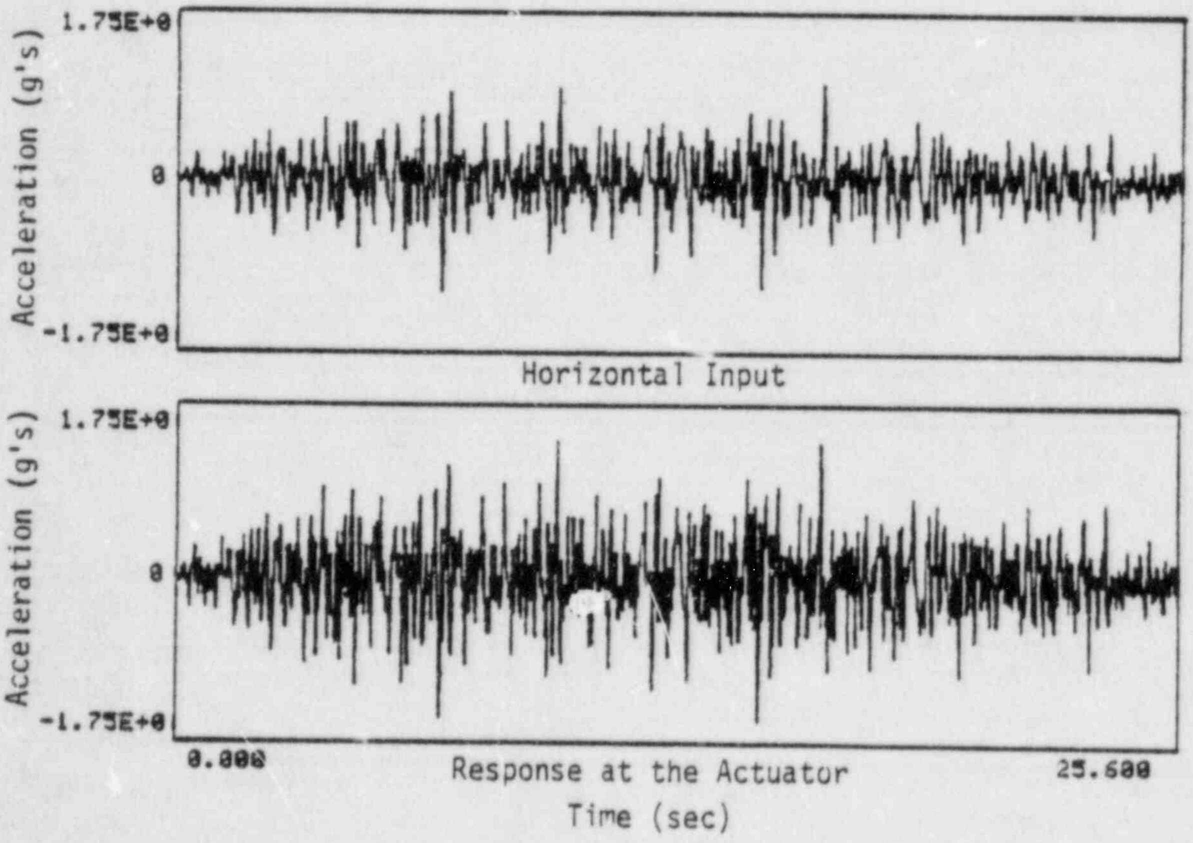


b) Coherence

Figure 5.1-4 Broadband Random Structural Identification, 0.2 g rms Y-Input, Y-Response at Actuator Motor, Flexible Supports, Vertical Table Fixed

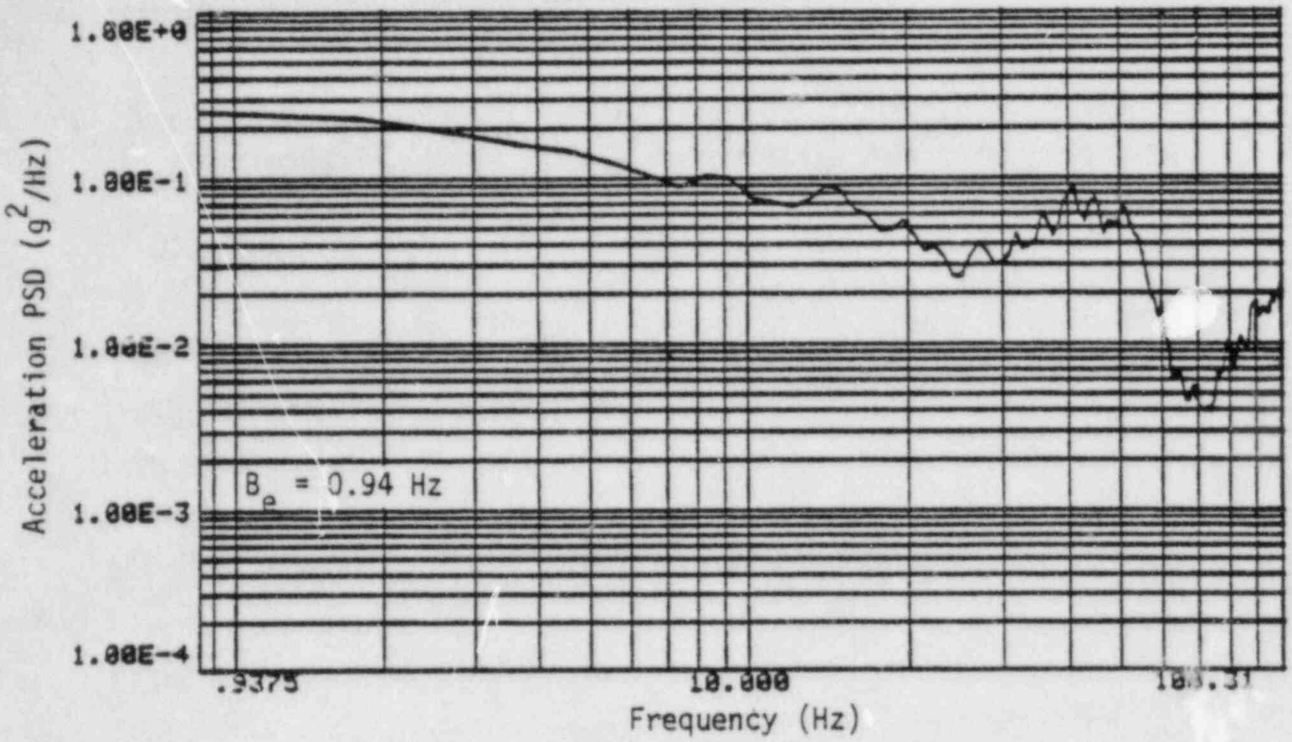


a) Rigid

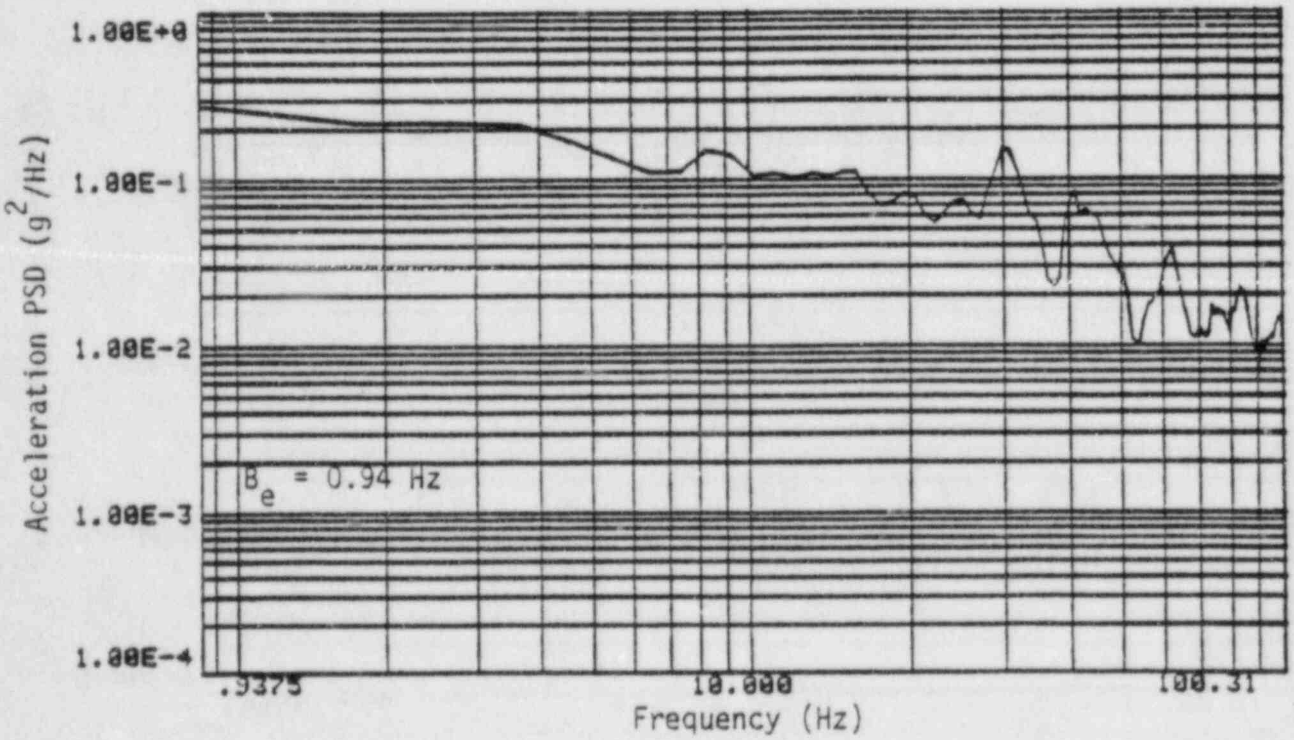


b) Flexible

Figure 5.2-1 Acceleration Time Histories for R.G. 1.60 Earthquake For Two Mounting Configurations

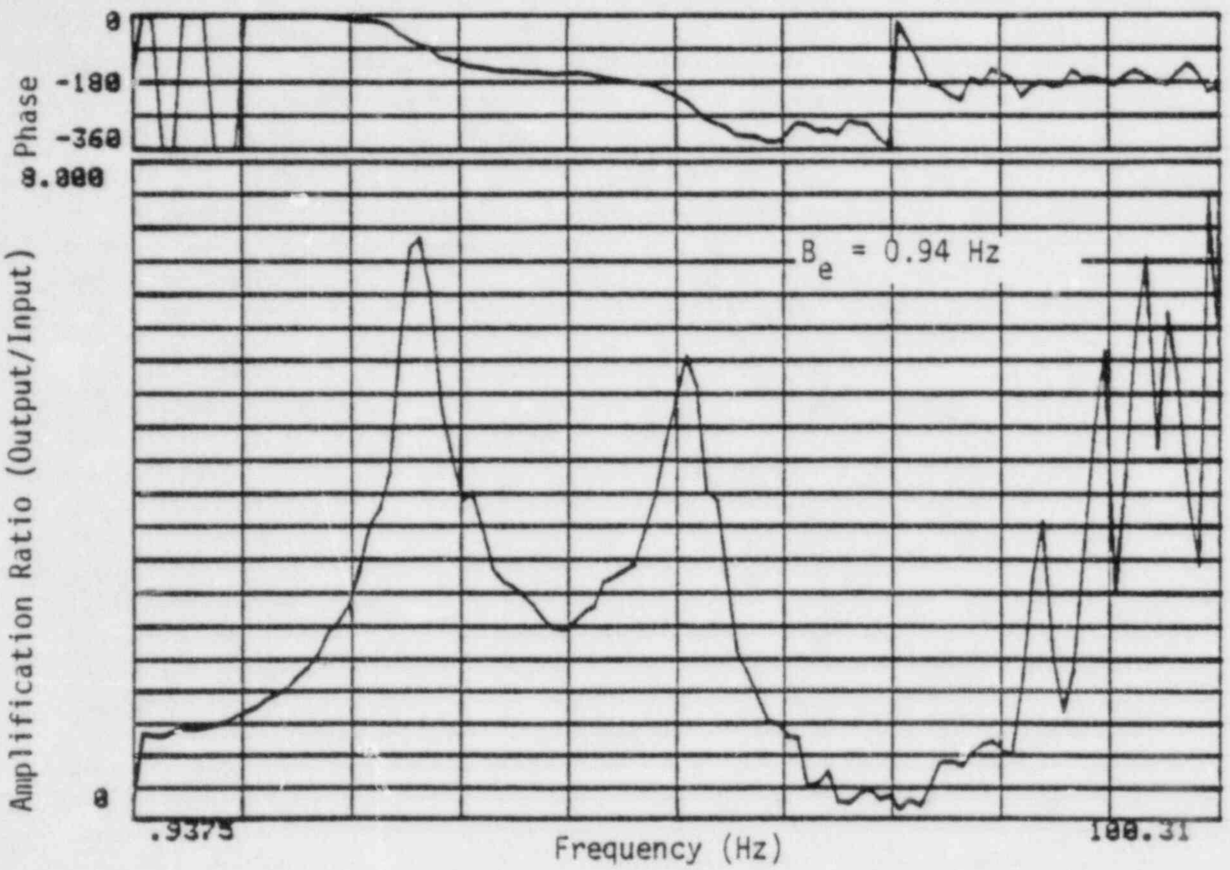


a) Rigid

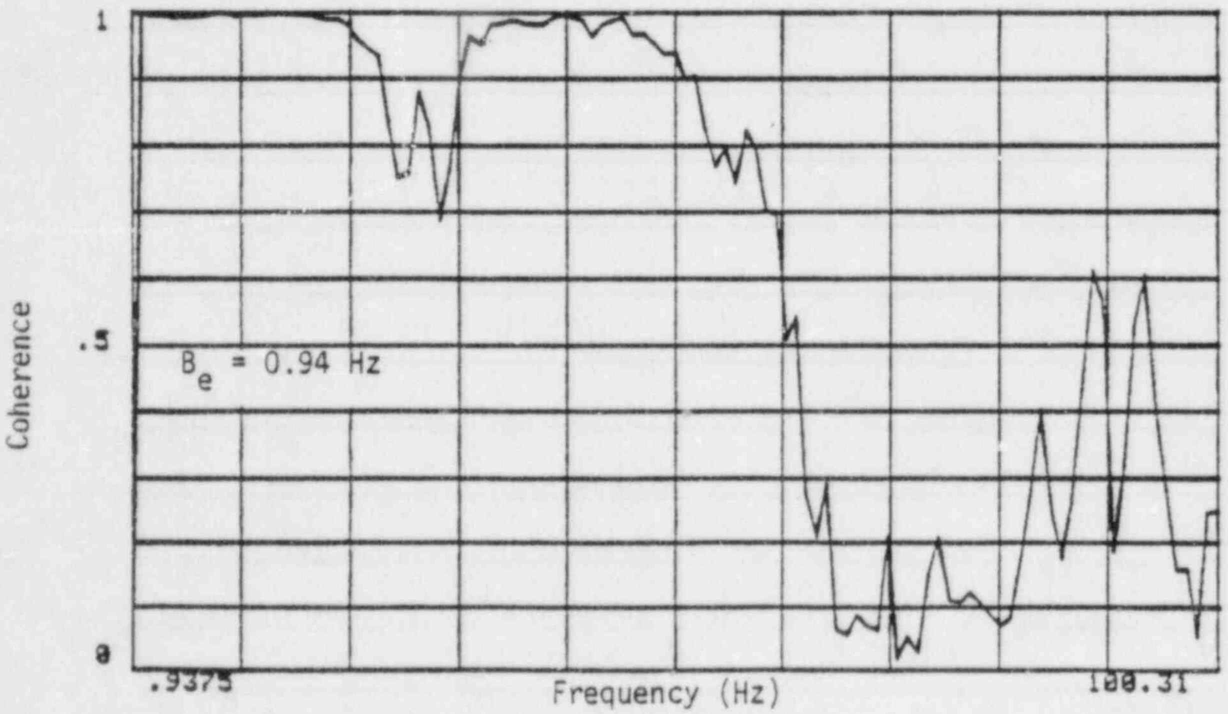


b) Flexible

Figure 5.2-2 Actuator Response Acceleration PSD's for R.G. 1.60 Earthquake For Two Mounting Configurations

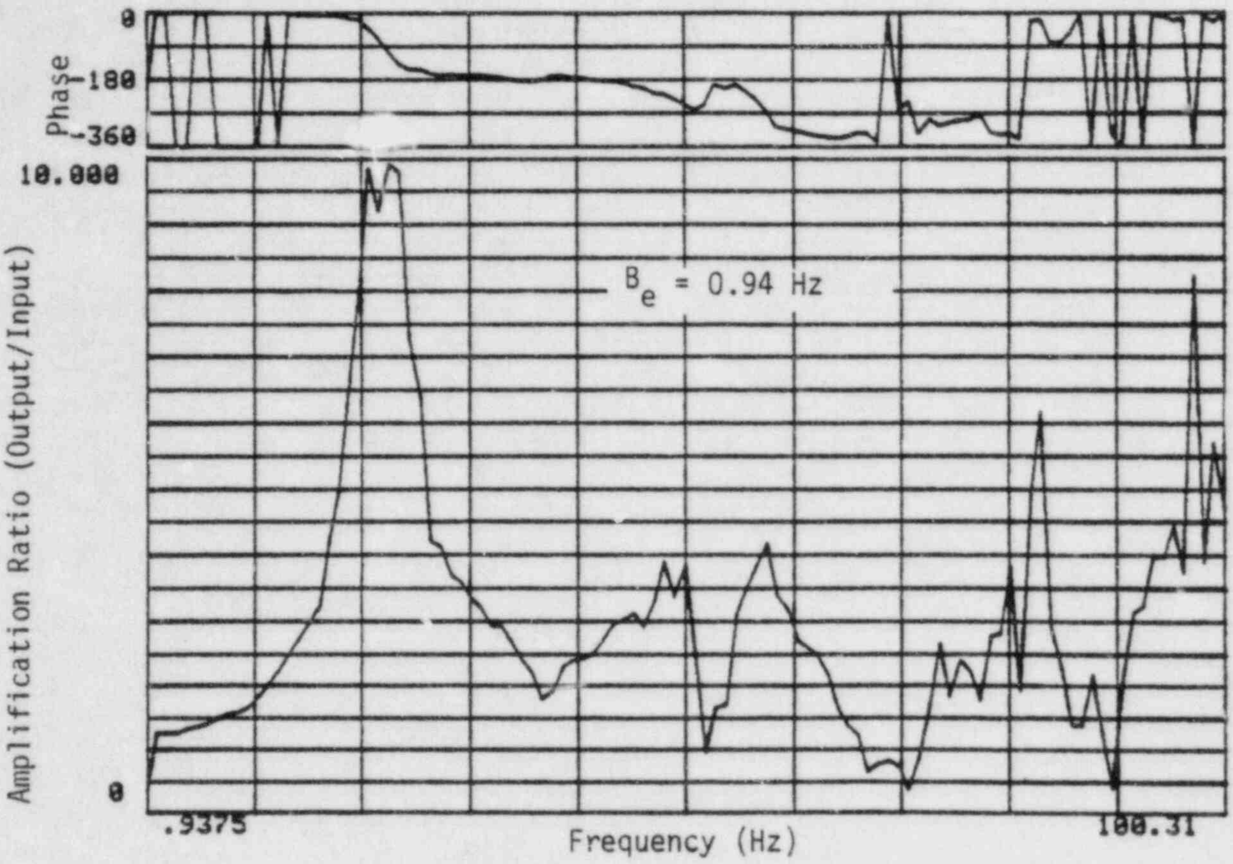


a) Transfer Function

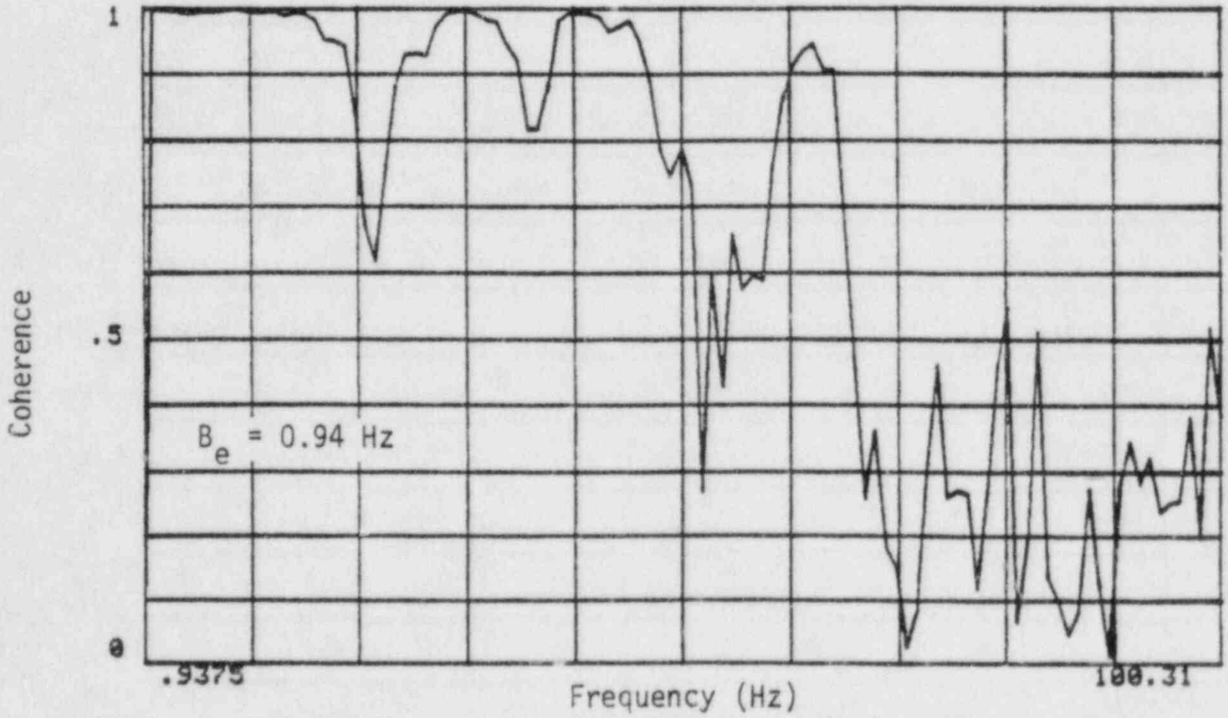


b) Coherence

Figure 5.2-3 Actuator Response for Rigid Mounting Configuration and a R.G. 1.60 Earthquake, Y-Z Input



a) Transfer Function



b) Coherence

Figure 5.2-4 Actuator Response for Flexible Mounting Configuration and a R.G. 1.60 Earthquake Y-Z Input

From the time histories it can be seen that the response at the actuator follows the input very closely for the rigid support. For the flexible support condition a higher frequency oscillation is superimposed on the earthquake motion, i.e., some filtering is taking place. This can also be seen from the PSD's in Figure 5.2-2, where the flexible support condition results show a definite peak at approximately 30 Hz compared to the rigid support PSD. The transfer function [Figures 5.2-3(a) and 5.2-4(a)], compare very favorably with the swept sine results, Figure 4.1-2. The frequencies for the R.G. 1.60 excitation test results are slightly lower as a result of the increased excitation level. However, the transfer function amplitudes are somewhat higher which is the opposite of what is expected. It appears that some differences of table interaction may influence the results. The coherence functions show that the results are in fact a result of the input motion.

In general a rigid support will produce responses that closely follow the input. This is good if the base motion is accurately defined with respect to the amplitude and frequency content. A typical line mounted piece of equipment will be subjected to a filtered signal as demonstrated by the flexible support testing. On the other hand, this motion is usually accounted for in present specifications for rigid mounts by increasing the input signal to match that at the specimen location in the pipe system.

5.3 Cross-Axis Response

Another problem encountered in qualification testing is the influence of cross-axis coupling of modes of the test item. A typical earthquake consists of three statistical independent displacements at a given location of the foundation of the plant. The resulting motion of a device mounted at an elevated location within the plant can be six degrees of motion. This is a result of multisupport spatial and time differences of motion at the various support locations. In the seismic qualification process an approximation must be made of this motion. The earliest testing consisted of uniaxial or correlated biaxial testing. Subsequent to this time both independent biaxial and triaxial test machines have been developed and used. The necessity of requiring multiaxial independent testing is still being discussed [1,7].

Due to the physical nature of the particular valve tested (i.e., stem at 45° and off center actuator motor), there was significant cross-axis coupling of the test item. Figure 5.3-1 shows the time history of a R.G. 1.60 vertical axis only run. All the accelerations are shown at the same amplitude scale for easy comparison. The response is measured at the actuator motor in both horizontal directions. There is significant X-axis (perpendicular to the axis of the pipe) and minor Y-axis (along the axis of the pipe) response. Each of the responses are typical of narrowband random signals, which can also be seen from the corresponding response PSD's, Figure 5.3-2.

From similar runs it was determined that the primary interaction was between horizontal and vertical responses and excitation. There was little cross-axis coupling between the two horizontal directions. Consequently, for this test item the use of a biaxial, horizontal and vertical axes, simulator was adequate. For other test items it is more applicable that biaxial testing in two horizontal axes is appropriate.

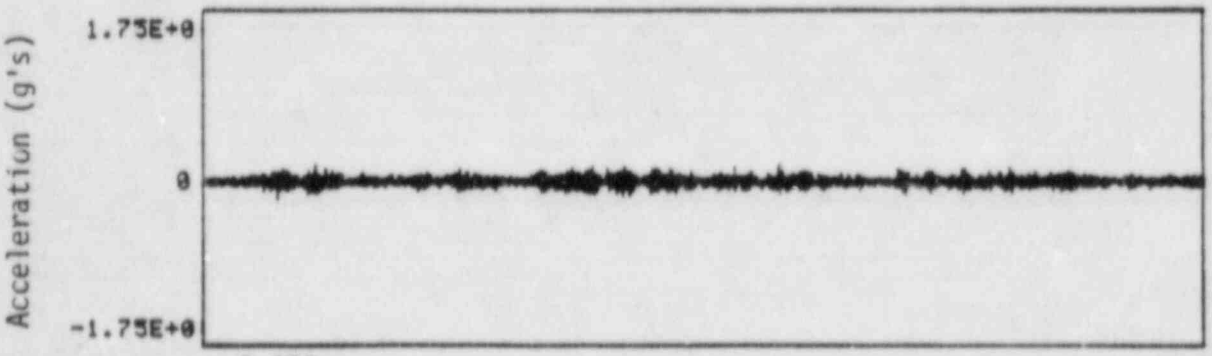
5.4 Qualification Procedures

Qualification testing of nuclear plant line-mounted equipment has typically been performed using narrowband excitation. Test waveforms have included sine dwells, swept sine, and sine beats with from five to ten cycles per beat. Due to the filtering characteristics of the piping structures they have provided a reasonable, although sometimes overly conservative, approximation of the actual motion the item might see when subject to earthquake excitation. Bhargara [10] has recently recommended a single axis sine test sequence for testing of a valve for boiling water reactors. The test procedure includes swept sinusoidal excitation to account for normal plant vibrations and small magnitude loading. In addition, sine beat tests are to be performed at a level so that the maximum calculated acceleration at the actuator, c.g., is obtained at frequencies no more than one-third octave apart. Justification of the proposed test method is included [10].

Some qualifications have been performed with broadband random input. The required response spectra are often times strongly frequency

a) Vertical Input

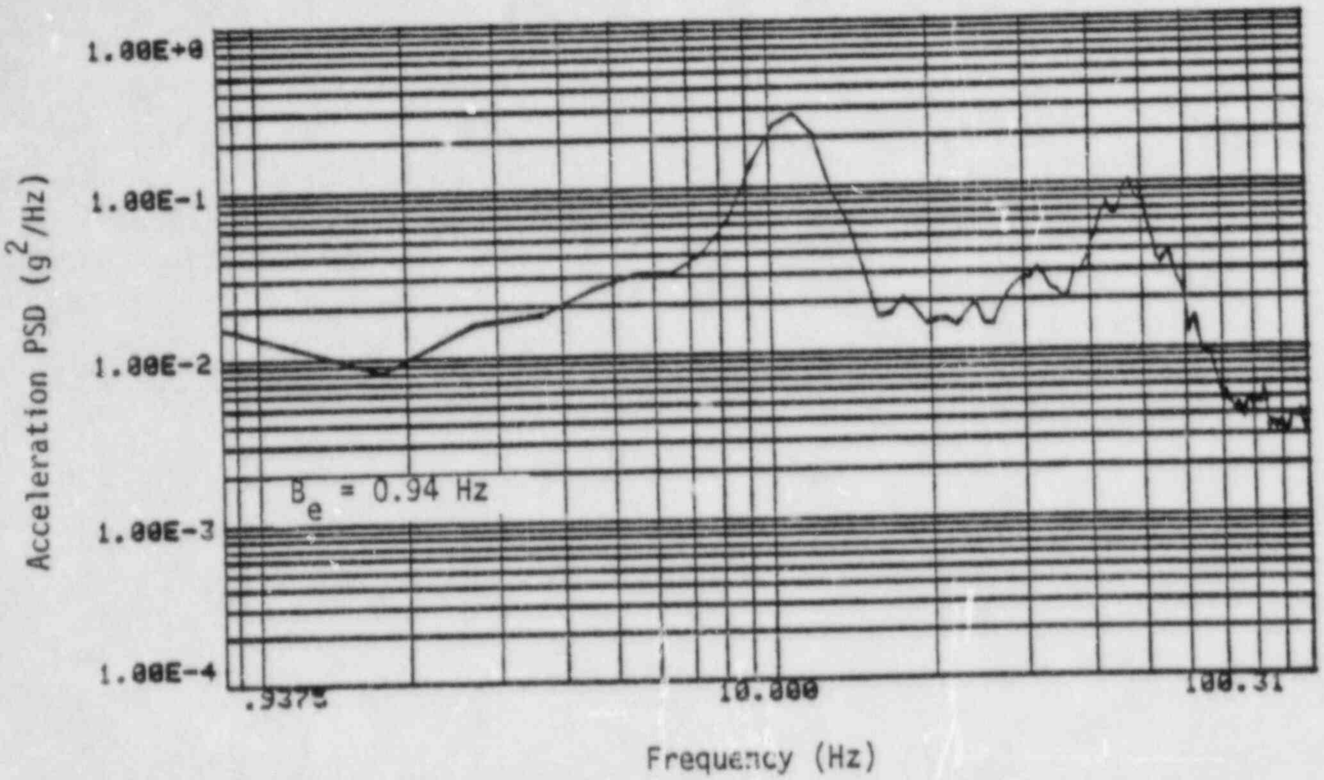
b) X-Axis Actuator Response



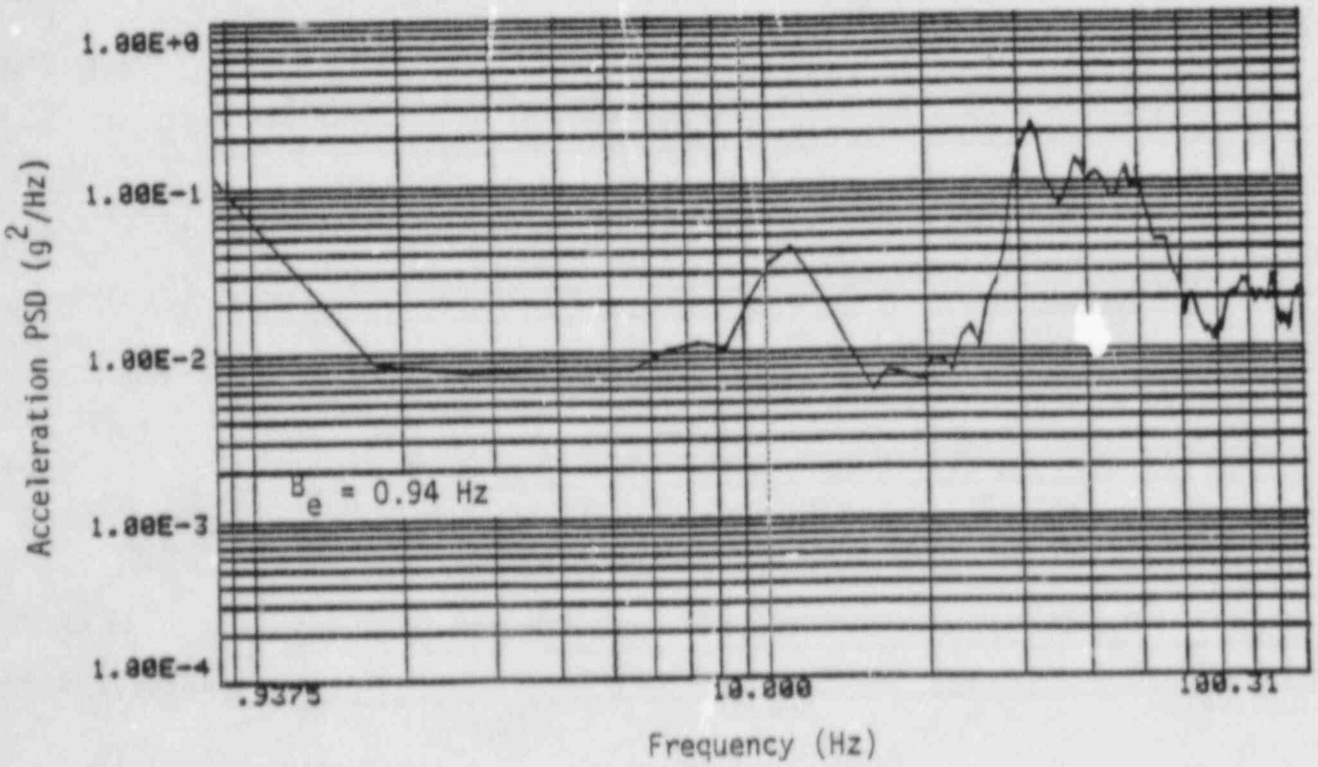
c) Y-Axis Actuator Response

Time (sec)

Figure 5.3-1 Time Histories of Vertical Axis Only R.G. 1.60 Earthquake



a) X-Axis Response



b) Y-Axis Response

Figure 5.3-2 Actuator Horizontal Response Acceleration PSD's for Vertical Axis Only R.G. 1.60 Earthquake dependent to account for the piping characteristics. Multiaxial excitation is most easily done using random excitation although correlated biaxial sine tests have been specified.

The results herein indicate that narrowband random testing be considered as an alternative test procedure for both swept and dwell testing where applicable. From both the analog circuit and valve testing it has been demonstrated that the response of a pipe mounted item will be dominated by narrowband response. Therefore it seems reasonable that for rigidly mounted valves a narrowband random input is applicable. If narrowband random dwell testing is used, it is important that the center frequencies be spaced closely enough to account for forcing function frequencies and test item resonances, the same as sine beat and sine dwell testing. One positive aspect of the swept testing is that no holes are left in the frequency of excitation as with dwell testing. The bandwidth of the narrowband random testing can be adjusted to overlap if required.

The relative severity of the sine and narrowband random testing is dependent on the most probable failure mode. If the failure is primarily RMS amplitude dependent, the sine testing would appear to be more severe, see Section 2.2. On the other hand the narrowband random test would appear to be more severe for a failure governed by peak amplitude. Therefore the functional characteristics and failure mode should be considered when comparing test methods.

A requirement of the qualification procedure is that the valve be shown to function properly during the excitation. For dwell testing, both sine and random, it is possible to operate the test item during each frequency test. For the swept testing it becomes necessary to judge the frequency range where failure is most probable and operate the valve in that region. In practice this means that any narrowband random excitation would need to be prerecorded, so that conservative portions could be predetermined.

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ACKNOWLEDGEMENTS

The authors wish to express their sincere appreciation to several members of the SwRI staff who contributed to the conduct of this program and preparation of the report.

Mr. F. R. Pitman provided much of the experimentation. Mr. V. J. Hernandez provided art work for the report. Ms. R. H. Rivas and H. M. Ruttan provided typing and editorial assistance.

Gratitude is also expressed for the efforts of the following colleagues who have served on the Peer Review Panel for this report. Their comments contributed significantly to its content.

Fred B. Safford - Agbabian Associates
Conway Chan - Electric Power Research Insitute
Alois J. Hartman - Westinghouse Electric Co.
Jim Hunter - EG&G, INEL
Paul Ibanez - ANCO Engineers, Inc.
George Shipway - Wyle Laboratories
Donald K. Henrie - General Electric Company

A special acknowledgement is extended to Mr. David H. Therneau and he Rockwell International Flow Control Division for donation of the lve specimen used in this study.

NRC FORM 335
(2-84)
NRCM 1102,
3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

SEE INSTRUCTIONS ON THE REVERSE

1. REPORT NUMBER (Assigned by TIDC, add Vol. No., if any)
NUREG/CR-3892
Vol. 1

2. TITLE AND SUBTITLE
A Research Program for Seismic Qualification of Nuclear Plant Electrical and Mechanical Equipment:
Task 1 - Survey of Methods for Equipment and Components; Evaluation of Methodology; Qualification Methodology for Line Mounted Equipment

3. LEAVE BLANK

4. DATE REPORT COMPLETED
MONTH | YEAR

5. AUTHOR(S)
D. Kana, E. Z. Polch, D. J. Pomerening, J. C. Simonis, J. E. Unruh

6. DATE REPORT ISSUED
MONTH: August | YEAR: 1984

7. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Southwest Research Institute
Post Office Drawer 28510
San Antonio, TX 78284

8. PROJECT/TASK/WORK UNIT NUMBER
SwRI-6582-001

9. FIN OR GRANT NUMBER
FIN B7087
Contract NRC-04-81-185

10. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Division of Engineering Technology
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555

11a. TYPE OF REPORT
Formal technical

b. PERIOD COVERED (Inclusive dates)

12. SUPPLEMENTARY NOTES

13. ABSTRACT (200 words or less)

The Research Program for Seismic Qualification of Nuclear Plant Electrical and Mechanical Equipment has spanned a period of three years and resulted in seven technical summary reports, each of which covered in detail the findings of different tasks and subtasks, and have been combined into five NUREG/CR volumes.

Volume 1 comprises three parts. Part I reviews the methods currently utilized for seismic qualification of nuclear plant equipment with emphasis on qualification by testing. In this review various anomalies that are assocated with qualfiication are identified. Part II provides an in-depth evaluationof the technical issues/anomalies previously identified. Part III provides an evaluationof the method applicable to line mounted items; e.g., valves.

14. DOCUMENT ANALYSIS – a. KEYWORDS/DESCRIPTORS
Qualification, Seismic
Seismic Qualification
Analytical Test Methodology

b. IDENTIFIERS/OPEN-ENDED TERMS

15. AVAILABILITY STATEMENT
Unlimited

16. SECURITY CLASSIFICATION
(This page)
Unclassified
(This report)
Unclassified

17. NUMBER OF PAGES

18. PRICE