Atomic Energy Control Board
Commission de contrôle de l'énergie atomique

R-7

Regulatory Document

Requirements for Containment Systems for CANDU Nuclear Power Plants

A Regulatory Policy Statement

Effective date: February 21, 1991

Canada

b1790766

TABLE OF CONTENTS

This document is part of a set of regulatory documents
relating to the safety requirements for CANDU nuclear power plants:

R–7, *Requirements for Containment Systems for CANDU Nuclear Power Plants*
R–8, *Requirements for Shutdown Systems for CANDU Nuclear Power Plants*
R–9, *Requirements for Emergency Core Cooling Systems for CANDU Nuclear Power Plants*

These documents apply to reactors licensed for construction after January 1, 1981.

REQUIREMENTS FOR CONTAINMENT SYSTEMS FOR CANDU NUCLEAR POWER PLANTS

1. DEFINITIONS*

In this document,

"closed system" means a piping system which penetrates and forms a closed loop or an enclosed volume either inside or outside the containment structure. For closed systems inside containment, the fluid in the system does not directly communicate with either the primary coolant or the containment atmosphere; (*système fermé*)

"containment envelope" means structures and appurtenances which provide a pressure-retaining barrier to prevent or limit the escape of any radioactive matter that could be released from the fuel elements, as a result of a failure in a fuel cooling system; (*enceinte de confinement*)

"containment structure" means the concrete portion and embedded parts of the containment system; (*structure de confinement*)

"fuel cooling system" means any cooling system whose failure has the potential for release of radioactive material in excess of the limits given in the reference. Included would be the primary heat transport system, any booster fuel cooling system, and the fuelling machine cooling system. Excluded would be the irradiated fuel bay cooling system; (*système de refroidissement du combustible*)

"minimum allowable performance standards" means the set of operating limits or the range of conditions established for components or subsystems which define the minimum acceptable states for those components or subsystems as credited in the safety analyses; (*normes de rendement minimal admissible*)

"primary heat transport system" means that system of components which permit the transfer of heat from the fuel in the reactor to the steam generators or other heat exchangers employing secondary cooling. For purposes of this document, it does not necessarily include auxiliary purification and pressure control subsystems; (*circuit caloporteur primaire*)

"special safety system" means one of the following systems: shutdown systems, containment system, emergency core cooling system. (*système spécial de sûreté*)

2. BASIC REQUIREMENTS

2.1 All water-cooled nuclear power reactors shall be installed within a containment structure. All piping which is part of the main circuit of the primary heat transport system, excluding boiler tubing, shall be totally within the containment structure.

2.2 (a) Except as noted in paragraph (b), all equipment required for correct operation of the containment system shall be considered to be part of that system and shall meet all requirements of this document. This shall include:

(i) the containment structure and appurtenances,

(ii) equipment required to isolate the containment envelope and assure its completeness and continuity following an accident,

(iii) equipment required to reduce the pressure or the free radioactive material within the containment envelope, and

(iv) equipment required to limit the release of radioactive material from the containment envelope following an accident.

---

* These definitions do not constitute a complete list of terms used in this document, but are included to clarify the meaning of some terms for the assistance of the reader. A more comprehensive list of definitions of terms relating to CANDU nuclear power plants is available from the Canadian Standards Association (CSA), *Manual of Definitions for CSA Nuclear Standards Use by CSA Technical Committees*, CSA–N9409A–1989.

(b) Equipment required to supply compressed air, electrical power or cooling water to equipment for operation of the containment system shall be considered as safety support equipment. Such equipment shall meet all relevant requirements of this document with the exception of sections 3.8 and 3.13.

2.3 The containment system shall be considered to be a special safety system.

2.4 Procedures to ensure compliance with the requirements of this regulatory policy statement shall be prepared by the licensee and shall require the approval of the Atomic Energy Control Board (AECB) prior to the issuance of a construction approval (procedures relating to part 3) or an operating licence (procedures relating to parts 4 and 5)

3. DESIGN REQUIREMENTS

3.1 Containment Envelope

There shall be a clearly defined continuous containment envelope which is capable of limiting to an acceptably low value the release of radioactive material from the station for all postulated failures of a fuel cooling system as specified in Table 1. The boundary of this containment envelope shall be defined for all conditions which could exist in the operation or maintenance of the reactor, or following an accident.

3.2 Design Information

3.2.1 The Safety Report shall clearly state the values of, and bases for, the following containment system design parameters:

(a) positive design pressure(s);

(b) negative design pressure(s) where applicable, and

(c) the maximum allowable leakage rate at the positive design pressure.

3.2.2 Minimum allowable performance standards shall be defined for the containment system and shall be listed or referenced in the Safety Report and in the Operating Policies and Principles for the plant. The minimum allowable performance standards shall also be specified for all major equipment and subsystems necessary for correct operation of the containment system.

3.2.3 A report shall be submitted which clearly identifies the containment envelope as described in section 3.1.

3.3 Dose Limits under Accident Conditions

The containment system shall be capable of limiting the release of radioactive material such that the reference dose limits are not exceeded.*

3.4 Structural Integrity

3.4.1 The positive design pressure of each part of the containment envelope shall be not less than the highest pressure which could be generated in that part as a result of any postulated events specified in Tables 1 and 2 for which radioactive material may be released into the containment envelope.

3.4.2 The negative design pressure of each part of the containment envelope shall not be greater than the lowest pressure which could be generated in that part as a result of any postulated event as specified in Tables 1, 2, 3 and 4.

3.4.3 It shall be shown that, for all events specified in Tables 1, 2, 3 and 4, the structural integrity of containment will not be impaired to a degree that consequential damage to reactor systems could result.

3.4.4 It shall be shown that, for all events specified in Tables 1, 2 and 3, no damage to the containment structure will occur.

3.5 Leakage Criteria

3.5.1 The maximum allowable leakage rate from the containment envelope shall be the value used in the safety analyses which demonstrate that the reference dose limits are not exceeded.

3.5.2 A test acceptance leakage rate shall be established, giving the maximum acceptable leakage rate under actual measurement tests. The margin between the maximum allowable leakage rate defined in subsection 3.5.1 and the test acceptance leakage rate shall require approval by the AECB prior to the first leakage rate tests.

---

* This regulatory document does not define comprehensive requirements for safety analysis and reference dose limits. The reference dose limits referred to in section 3.3 are those contained in the reference, or any subsequent AECB regulatory document, or as otherwise agreed in writing between the licensee and the AECB.

3.6 Environmental Requirements

3.6.1 All parts of the containment system which may be required to operate, or to continue operating, in response to any event specified in Tables 1, 2, 3 and 4 shall be designed to meet all necessary performance requirements while subjected to the most severe environmental conditions which could be present when or before such operation is required. These conditions may include, but are not necessarily limited to, the effects of debris, steam, water, high temperature, radiation, and pressure differentials.

Qualification is required for all containment equipment which may be required to operate, or to continue operating, following exposure to any of the above conditions. Qualification shall consist of tests to demonstrate to the extent practicable that the type of equipment can operate under conditions similar to those which would exist during or following the events listed in Tables 1, 2, 3 and 4. Where such tests are impracticable, analysis is required to demonstrate that this requirement is met.

3.6.2 The containment system shall be designed such that, for all events specified in Tables 1, 2, 3 and 4, dynamic effects or jet forces caused by the event cannot result in impairment of the containment system to an extent that the relevant requirements in subsections 3.3, 3.4 and 3.5 would not be met.

3.7 Availability Requirements

3.7.1 The containment system shall be designed such that the fraction of time for which it is not available can be demonstrated to be less than 10^{-3} years per year. The system shall be considered available only if it can be demonstrated to meet all the minimum allowable performance standards as defined in accordance with subsection 3.2.2.

The availability of safety support equipment necessary for correct operation of the containment system shall be commensurate with the availability requirements of the containment system.

Availability calculations to demonstrate that this requirement can be met shall be included or referenced in the Safety Report. Such calculations shall be based on direct experience or reasonable extrapolations therefrom.

3.7.2 The design of the containment system and safety support equipment shall take into account the long-term reliability requirements of those components which must continue to function following an accident. Standards for the long-term reliability of such components shall be prepared and shall require approval by the AECB prior to the issuance of a construction approval.

3.7.3 The design shall have sufficient redundancy such that no failure of any single component of the containment system can result in impairment of the system to an extent that it will not meet its minimum allowable performance standards under accident conditions.

This requirement does not apply to components which are not required to change state and which do not depend on safety support equipment in order to perform their design functions, provided that they are designed, manufactured, inspected and maintained to standards acceptable to the AECB.

3.7.4 Correct operation of the containment system following an accident shall not be dependent on power supplies from the electrical grid or from the turbine generators associated with any reactor unit within that containment system.

3.7.5 As far as practicable, all containment equipment shall be designed such that its most probable failure modes will not result in a reduction in safety.

3.7.6 As far as practicable, the design shall be such that all maintenance and unavailability testing which may be required when the containment is required to be available can be carried out:

(a) without impairment of the containment envelope, and

(b) without a reduction in the effectiveness of the containment system below its minimum allowable performance standards.

3.7.7 As far as practicable, the design shall be such that a failed component can be put into a safe state, or such that the failure can be converted to a safe failure in some other manner.

3.7.8 The design shall be such that all necessary actions of containment equipment which are initiated by automatic control logic in response to an accident can also be initiated manually from the appropriate control room.

3.8 Separation and Independence Requirements

3.8.1 As far as practicable, the containment system shall be physically and operationally independent from other special safety systems. No equipment which is part of the containment system shall be used as part of another special safety system.

3.8.2 As far as practicable, the containment system shall be independent from all process systems. This requirement does not apply to equipment discussed in subparagraphs 2.2(a)(iii) and (iv) provided that such equipment is normally operating when the reactor is operating.

3.8.3 Design principles for separation of redundant instrument channels and the services to them, associated with the containment system, shall be prepared and shall require approval by the AECB prior to the issuance of a construction approval.

3.8.4 If subsystems of containment are considered to be independent for the purpose of the safety analyses, principles for separation and independence of such subsystems shall be prepared and shall require approval by the AECB prior to the issuance of a construction approval.

3.9 Requirements for Penetrations of the Containment Structure

Piping systems which penetrate the containment structure shall be designed to meet the requirements specified in the Appendix.

3.10 Containment Atmosphere Control

3.10.1 Systems shall be incorporated into the containment design to assist in the control of the internal pressure and to control the release of radioactive material to the environment following an accident.

3.10.2 Provision shall be made for controlling the concentration of hydrogen and/or oxygen following an accident to prevent explosion or deflagration, unless it is demonstrated that there is no possibility of such an explosion or deflagration as a result of any event specified in Table 1.

3.10.3 The design of the plant shall be such that, following an accident, it is possible to isolate all engineered sources of compressed air and other non-condensable gases leading into the containment atmosphere, other than those required for the operation of necessary equipment.

3.11 Shielding Requirements

3.11.1 The design of the containment system and associated equipment shall incorporate sufficient provision for shielding to ensure that radiation fields would not be excessive in areas of the plant to which access might be required following an accident.

3.11.2 A report demonstrating the adequacy of the shielding provisions* shall be prepared and shall specify:

(a) the postulated accident which results in the largest release of radioactive material inside the containment envelope;

(b) all areas to which access might be required following such an accident, with the frequency and duration of necessary access, and

(c) the maximum radiation fields expected in such areas when access might be required.

3.12 Status Monitoring Requirements

3.12.1 The design shall be such that the status of all important equipment can be monitored or inferred from the appropriate control room.

3.12.2 The design shall be such that any gross breach of the containment envelope can be readily and reliably detected.

3.13 Codes and Standards

3.13.1 The application for a construction approval shall identify any aspects of the design which fail to comply with the applicable requirements of the following codes and standards:

(a) CSA N287: Series on *Concrete Containment Structures for CANDU Nuclear Power Plants*, and

(b) CAN3–N285.0: *General Requirements for Pressure-Retaining Systems and Components in CANDU Nuclear Power Plants.*

All exceptions to the requirements of these standards shall require approval by the AECB prior to their implementation.

---

* Equipment required only for shielding purposes need not be considered as part of the containment system.

3.13.2 A list of additional codes and standards to be applied to the containment system and the extent of their application shall be prepared and shall require approval by the AECB prior to the issuance of a construction approval.

3.14 Seismic Requirements

All parts of the containment system credited in the safety analysis following a design basis seismic ground motion for that plant site shall be designed to remain fully functional following such an event.

4. OPERATING REQUIREMENTS

4.1 Requirements for Normal Operation

4.1.1 The containment system shall not be intentionally made unavailable, unless all of the following conditions are met:

(a) all reactors within the containment envelope are in a guaranteed shutdown state approved by the AECB,

(b) all reactor cooling systems are sufficiently cooled and depressurized in accordance with procedures approved by the AECB, and

(c) all irradiated fuel within the containment envelope is adequately cooled and has an alternate cooling supply available.

Procedures for intentionally making the containment system unavailable shall be prepared and shall require the approval of the AECB prior to the issuance of an operating licence.

The containment system shall be considered to be available only when it meets all the minimum allowable performance standards as defined in accordance with subsection 3.2.2.

4.1.2 Procedures for taking corrective action, in the event that the containment system is found to be impaired when the conditions mentioned in subsection 4.1.1 are not met, shall be prepared and shall require approval by the AECB prior to the issuance of an operating licence.

4.1.3* If any component of the containment system is found to be inoperable or impaired below its minimum allowable performance standards, the component and its associated equipment shall, as far as practicable, immediately be put in a safe condition, except as approved in accordance with subsection 4.1.2.

4.1.4* As far as practicable, maintenance on a containment system component shall be carried out only when that component and its associated equipment have been put in a state which does not reduce the availability of the containment system.

4.1.5* If redundant components require maintenance, each component shall be thoroughly tested following its maintenance prior to the start of work on a subsequent component.

4.1.6 When maintenance on a component is completed, it shall be tested to the extent practicable to demonstrate that it and its associated equipment function in accordance with design requirements.

4.1.7 The standard of maintenance shall be such that the reliability and effectiveness of all equipment, as claimed in the Safety Report and other documentation in support of an operating licence, are assured.

4.2 Requirements for Accident Conditions

If operator action is required for actuation of any containment equipment, all of the following requirements must be met:

(a) there shall be instrumentation to give the operator clear and unambiguous indication of the necessity for operator action;

(b) the reliability of such instrumentation shall be commensurate with the requirements for availability of the containment system as specified in section 3.7. If indication of only a single parameter is required, the instrumentation shall be part of the containment system;

(c) there shall be 15 minutes available following such clear and unambiguous indication before the operator action is required, and

(d) there shall be clear, well-defined and readily available operating procedures to identify the necessary actions.

---

* Requirements 4.1.3, 4.1.4 and 4.1.5 do not apply during periods when the containment system has been made unavailable in accordance with procedures approved pursuant to subsection 4.1.1.

5. TESTING REQUIREMENTS

5.1 Commissioning Tests

5.1.1 Pressure Proof Tests

Prior to first criticality of any reactor, positive pressure proof tests shall be done to demonstrate the structural integrity of all parts of the containment envelope and the containment system. If the design specifications include a negative design pressure, a negative pressure proof test shall also be done.

Positive pressure proof tests shall be done at a pressure not less than 1.15 times the positive design pressure for each part of the containment envelope.

Negative pressure proof tests shall be done at a pressure not greater than the negative design pressure.

If any of the above tests are impracticable, testing of representative equipment in a laboratory may be accepted, if approved by the AECB.

5.1.2 Leakage Rate Tests

Prior to first criticality of any reactor, the leakage rate of its containment envelope shall be measured to demonstrate that it is not greater than the test acceptance leakage rate. Measurements shall be made at a range of pressures up to and including the positive design pressure for each part of the containment envelope. The test shall be conducted with containment components in a state sufficiently representative of those which would exist following an accident to demonstrate that the appropriate leakage rate would not be exceeded under such conditions.

Testing of individual penetrations, isolating devices and airlocks shall be done for those penetrations for which it is necessary to obtain baseline leakage measurements against which the future in-service leakage tests specified in subsection 5.2.4 may be compared.

5.1.3 Tests of Containment Equipment

Prior to first criticality of any reactor, tests of the containment system equipment shall be performed to verify that all design requirements have been achieved. Exceptions to this requirement will be allowed only if it is shown to the satisfaction of the AECB that some operational characteristics are impracticable to demonstrate under non-accident conditions or that such tests would have a detrimental effect on safety.

5.1.4 Wiring Tests

Prior to first criticality of any reactor, tests shall be carried out on all electrical wiring associated with the containment system to demonstrate that all connections are in accordance with the design.

5.2 In-Service Tests and Inspections

5.2.1 Pressure Proof Tests

Pressure proof tests, as specified in subsection 5.1.1, shall be repeated following any major modification of the containment envelope or after the containment system has been subjected to elevated pressure differentials as a result of an accident or after the containment system has been subjected to any severe environmental effects.

5.2.2 Leakage Tests

In-service leakage rate tests shall be carried out in accordance with one of the following alternative methods:

(a) a leakage rate test shall be carried out at full design pressure at least once every three years to demonstrate that the measured leakage rate is not greater than the maximum allowable leakage rate. If the measured leakage rate is in excess of the test acceptance leakage rate, the frequency of such tests shall be increased to once every two years, or

(b) a leakage rate test shall be carried out at a frequency of not less than once per two years to demonstrate that the leakage rate is not greater than the maximum allowable leakage rate. Such tests may be carried out at reduced or negative pressures. However, if the test results, when extrapolated to full design pressure, indicate leakage in excess of the test acceptance leakage rate, a leakage rate test at the full positive design pressure shall be carried out to demonstrate that the maximum allowable leakage rate is not exceeded. A leakage test at full design pressure shall be carried out a minimum of once per six years in any case.

In addition to the above routinely scheduled leakage rate tests, a leakage rate test at the full design pressure shall be performed in conjunction with any pressure proof test required under subsection 5.2.1.

5.2.3 Containment Equipment

To the maximum extent practicable (see subsection 5.1.3), tests to demonstrate that containment equipment meets its minimum allowable performance standards shall be carried out at a frequency of not less than once per six years.

5.2.4 Tests of Penetrations and Isolating Devices

An in-service test program for penetrations, airlocks and isolating devices shall be prepared. The program shall detail for each type of penetration, isolating device and airlock to be tested, the nature of the test, test frequency, and leakage acceptance criteria. This program shall require the approval of the AECB prior to the issuance of an operating licence.

5.2.5 Visual Inspections

External visual inspections of the containment envelope, including appurtenances and penetrations shall be carried out in conjunction with each of the tests required by subsections 5.2.1, 5.2.2 and 5.2.4.

The interior of this envelope shall be visually inspected at a frequency and to an extent approved by the AECB prior to the issuance of an operating licence.

5.2.6 Reporting Requirements

The results of all in-service tests and inspections of the containment system shall be reported in the annual reports for the station.

5.3 Availability Tests

5.3.1 All containment equipment shall be monitored or tested at a frequency which is adequate to demonstrate compliance with the availability requirements specified in subsection 3.7.1.

5.3.2 A report on the availability of the containment system shall be included in each annual report on the operation of the station. This report shall include:

(a) a statement of the total fraction of time in the year during which the containment system was not demonstrated to be available, as defined in subsection 3.7.1. Only periods during which the containment system is intentionally made unavailable, in accordance with the conditions of section 4.1, shall be excluded from such calculations,

(b) a comparison of the failure modes and failure frequencies observed in operation of the station with the failure modes and failure frequencies used in the availability calculations prepared in accordance with subsection 3.7.1, and

(c) availability calculations sufficient to demonstrate that the availability requirement of subsection 3.7.1 can continue to be satisfied based on observed failure modes and failure frequencies.

REFERENCE

D.G. Hurst and F.C. Boyd, "Reactor Licensing and Safety Requirements", AECB–1059, June 1972.

TABLES *

TABLE 1

1. Failure of any pipe or header in any fuel cooling system
2. Failure of a pressure tube and the associated calandria tube
3. Failure of an end fitting
4. Fuel channel flow blockage
5. Failure of a fuelling machine to replace a closure plug
6. Inadvertent opening of pressure relief or control valves on the primary heat transport system or associated systems
7. Failure of steam generator tubes
8. Any of events 1 to 7 occurring coincidentally with impairment of the emergency core cooling system
9. Inadvertent opening of pressure relief valves connecting to a vacuum building

TABLE 2

Any of events 1 to 7 in Table 1 accompanied by complete failure of dousing.

TABLE 3

Failure of any pipe in the steam generator feedwater or steam systems.

TABLE 4

Failure of any pipe in the steam generator feedwater or steam systems accompanied by complete failure of dousing.

* In these tables, "failure" means both total failure and partial failure.

APPENDIX

REQUIREMENTS FOR METAL EXTENSIONS OF THE CONTAINMENT ENVELOPE

1. CODE REQUIREMENTS

Systems or portions of systems which form part of the containment envelope shall be constructed to the requirements of the *ASME Boiler and Pressure Vessel Code*, Section III, Division 1, Subsection NC (Class 2 components) or Subsection NE (Class MC components) except for:

(a) those systems whose process requirements are Class 1 or 2 in accordance with CAN3–N285.0;

(b) those closed systems inside the containment structure which have a design pressure greater than 0.5 MPa(g) and are continuously operated at or above the positive design pressure of the containment at all points in the system, and which can be monitored for leaks. Such systems may be constructed to the process systems requirements, but they shall be constructed to not less than the non-nuclear requirements of CSA B51.

Closed systems inside the containment structure which do not meet the requirements in paragraphs (a) and (b) may be built to the requirements of Class 3 if it can be shown to the satisfaction of the AECB that, due to smallness of size or other factors, the proposed design provides an adequate barrier.

2. ISOLATION

Piping systems shall be provided with isolation devices having redundancy, reliability, and performance capabilities which reflect the importance to safety of isolating the various types of piping systems penetrating containment. Where isolation in a piping system is provided by valves, provisions shall be made to test the valve operability periodically, to check that the valve leakage is within acceptable limits and to allow maintenance of the valve without causing a breach of the containment envelope. In order for a manual isolation valve to be considered closed, it shall be either locked closed or continuously monitored to show that the valve is in the closed position.

The various types of piping systems penetrating containment shall be provided with the following isolation unless it can be shown that, for a specific type of line, other isolation provisions would be acceptable.

2.1 Primary Heat Transport Auxiliary Systems Penetrating Containment

Each line that is connected to the primary heat transport system pressure boundary and that penetrates the containment structure shall be provided with two isolation valves in series. The valves shall normally be arranged with one inside and one outside the containment structure. If it can be shown that two valves inside the containment structure or two valves outside the containment structure can provide an equivalent barrier in certain applications, then this may also be an acceptable arrangement.

A check valve may be used as one of the isolation barriers but it shall be located inside the containment structure. Two check valves in series are not considered an acceptable barrier.

Where the valves provide isolation of the heat transport system during normal operation of the station, then both valves shall normally be in the closed position.

Systems directly connected to the heat transport system and which may be open during normal operation of the station shall also be provided with the same isolation as the normally closed system except that manual isolating valves inside the containment structure shall not be used. At least one of the two isolation valves shall be either an automatic isolation valve (for instance, a check valve) or a powered isolation valve operable from the control room.

For small lines of 25 mm in nominal diameter or less, a single closed isolation valve inside containment may be used provided the line is connected to a closed system outside containment.

The line up to and including the second isolation valve, or the first valve in the case of small lines 25 mm in nominal diameter or less shall be constructed to the requirements of Class 1 in accordance with CAN3–N285.0.

2.2 Systems Connected to Containment Atmosphere

Each line that connects directly to the containment atmosphere, that penetrates the containment structure, and that is not part of a closed system, shall be provided with two isolation barriers as follows:

(a) two automatic isolation valves in series for those lines which may be open to the containment atmosphere;

(b) two closed isolation valves in series for those lines that are normally closed to the containment atmosphere;

(c) one closed isolation valve for lines of 50 mm in nominal diameter or less, which are normally closed to the containment atmosphere and connected to an easily defined closed system outside containment.

The line up to and including the second valve, or the first valve in the case of paragraph (c), shall be part of the containment envelope and shall be constructed to the requirements of *ASME Code*, (Section III, Class 2).

2.3 Closed Systems

Closed systems inside or outside the containment structure which form part of the containment envelope and which meet the requirements of Class 2 and can be continuously monitored for leaks need no further isolation. All other closed systems shall be provided with a single isolation valve on each line penetrating containment. The valves shall be located outside containment as close as practicable to the containment structure. Valves required for process purposes may be used as the isolation valves for these closed loops.

2.4 Small Lines

For ductile piping of small bore, crimping of the pipe is a possible means of providing an isolation barrier instead of a valve. For this to be acceptable, the details of its application shall be submitted for approval in each case of its proposed use. In particular, the method of crimping, the location of the part to be crimped and the method of identifying the failed line shall be shown to be satisfactory. In the case of primary heat transport system instrument lines, the following extra conditions are required:

(a) space must be available for crimping the tubes where they penetrate through the containment structure.

(b) the quality of the lines is to be as good as the rest of the primary heat transport system.

(c) the relevant release limits must be shown not to be exceeded during the period in which the reactor is shut down consequent to the failure, and the crimping is executed, and

(d) any outflow from the breaks can be filtered before release to the atmosphere to control the escape of fission products.

DESIGN REQUIREMENTS, CRITERIA AND METHODS FOR SEISMIC QUALIFICATION OF CANDU NUCLEAR POWER PLANTS

by N. Singh and C.G. Duff

Abstract

This report describes the requirements and criteria for the seismic design and qualification of systems and equipment in CANDU nuclear power plants. Acceptable methods and techniques for seismic qualification of CANDU nuclear power plants to mitigate the effects or the consequences of earthquakes are also described.

1979 October

Atomic Energy of Canada Limited
Engineering Company

L'Énergie Atomique du Canada, Limitée
Société d'Ingénierie

Sheridan Park Research Community
Mississauga, Ontario L5K 1B2

AECL-6691

CONTENTS

ILLUSTRATIONS

TABLES

1. INTRODUCTION

Seismic design requirements for commercial structures and industrial plants have been invoked in Canada for many years through the National Building Code of Canada (NBCC), Reference 1, which is mandatory throughout Canada. The seismic design of nuclear power plants requires special consideration as a result of concern for the nuclear safety of the public. The seismic design philosophy for CANDU nuclear power plants is based on principles established by the Atomic Energy Control Board (AECB) of Canada. These have resulted in the formulation of requirements and criteria to ensure the integrity and operability of structures and components in the event of an earthquake. These requirements and criteria are being formulated in Canadian Standards Association Standard N289 (Reference 2). Pending this codification, approval by the AECB is required on a case-by-case basis.

This report describes the philosophy, requirements, criteria and acceptable design methods for the seismic design of systems, structures, and components for CANDU nuclear power plants to protect them from the consequences of earthquakes. It is written in the style of a Standard or Design Guide because its contents are directly applicable to the scope of such documents.

Structures, systems, equipment and components to be seismically qualified shall be qualified to the requirements and criteria stated or referenced in this report, and in accordance with the methods and procedures described or referenced in this document. Equipment not specifically required to be seismically qualified, but whose failure, deformation or dislocation could impair the performance of nearby safety-related systems is also covered.

2. DEFINITIONS

The following definitions, listed in alphabetical order, apply in the content of this document:

Assembly means a piece of electrical equipment comprising electrical modules mounted in or on a common enclosure, e.g., console, panel; frame, rack, etc..

Bracing means a structural element which provides additional stiffening or stability to the equipment or its support.

Component means the hardware located in a nuclear power plant, (e.g. pumps, vessels, valves, machinery, piping, etc.).

Damping is a measure of the energy dissipation in a vibrating body due to hysteresis, friction, impact, joint slippage, etc., and is defined by the damping ratio.

Damping Ratio (β) is the ratio of the damping coefficient to the critical damping coefficient for a single-degree-of-freedom oscillator or a normal mode.

Degrees-of-Freedom (DOF) means the minimum number of independent coordinates required to define completely the position of all parts of a system at any instant of time.

Note: A single-degree-of-freedom (SDOF) system is one where the position of the system can be defined in terms of a single coordinate. It is characterized by a single mass, structural stiffness and mode shape.

Design Basis Earthquake (DBE) means an artificial representation of the combined effects in the free-field at the location of the site, of a set of possible earthquakes having a sufficiently low probability of exceedence during the life of the plant, and expressed in the form of response spectra or a time-history.

Note: The DBE represents the maximum ground motion for the site which has a sufficiently low probability of being exceeded during the operating life of the nuclear power plant that unacceptable radioactivity releases can be avoided.

Dynamically Decoupled Systems means that the mass and structural properties of the supported system do not significantly change the dynamic response characteristics of the supporting structure.

Dynamic Analysis means a modal or direct integration analysis of the structure or components to determine its response to a dynamic forcing function.

Earthquake Level means the design earthquake, expressed as a Design Basis Earthquake or a Site Design Earthquake, to which selected critical systems, structures and equipment in a nuclear power plant must be designed, in order to provide additional assurance of performance of their safety function in the event of an earthquake.

Equipment is a non-specific term referring to components, assemblies modules, devices, etc..

Flexibility is the inverse of stiffness (see stiffness).

Floor Acceleration is the acceleration of a particular building floor or elevation or mounting location of interest, resulting from a specified seismic motion applied to the building structure.

Note: Normally, the limiting spectral acceleration value corresponding to the rigid frequency (see definition) represents the **maximum floor acceleration** (see Figure 2.1).

Floor Response Spectrum (FRS) means the response spectrum* for a particular floor (elevation) in a structure when the structure is subjected to the design seismic motion (DBE or SDE as applicable), see Figure 2.1.

Note: The FRS defines the response of equipment mounted on a particular floor (elevation) of a structure, when the structure is subjected to the design seismic motion.

Fragility Testing means vibration testing of equipment to determine its ultimate capability, i.e., the equipment is tested to the point where it can no longer perform its function, whether due to electrical or mechanical malfunction or physical deformation or destruction.

Free-field means the time-history record of the seismic ground motion as measured at the surface of the soil or rock, unaltered by the presence of large structures.

Ground Acceleration is the most common parameter for defining earthquake motion and is usually expressed in cm/sec^2 or "g" units. (Note: By international agreement, the value of g = 32.1739 ft/sec^2 = 980.665 cm/sec^2 = 980.665 gal has been chosen as the standard acceleration due to gravity).

Ground Response Spectrum means the response spectrum* which represents the response of a structure to the design seismic motion in the form of a time-history or a response spectrum.

Mass means the weight of the system being analyzed divided by the acceleration due to gravity.

Note: For the purpose of dynamic analysis, the mass of component, structure or system is usually assumed to act at one or a number of discrete points, (lumped-mass modelling).

Modal Mass of a system means the equivalent mass in a normal mode and is a measure of the mass associated with a particular mode.

Modal Participation Factor (Γ) is a number developed from a mathematical expression which utilizes the mass and mode shapes of a multi-degree-of-freedom system for evaluating the modal response of a particular mode of vibration, due to a particular excitation.

The Γ of a given mode is a measure of the relative strength of the response of the system in that mode.

* See definition

NOTES:

1. THE FREQUENCY DISTRIBUTION OF FLOOR MOTION REPRESENTS A PLOT OF FLOOR RESPONSE TO THE DESIGN BASIS SEISMIC GROUND MOTION. f_{n1}, f_{n2}, f_{n3}, ... ARE THE MODAL FREQUENCIES (EIGENVALUES) OF THE SUBJECT FLOOR (ELEVATION).

2. THE MAXIMUM FLOOR ACCELERATION IS ALWAYS GREATER THAN THE PEAK MODAL RESPONSE OF THE FLOOR SINCE IT INCORPORATES THE EFFECTS OF ALL MODAL RESPONSES.

3. RIGID COMPONENTS MOUNTED ON A BUILDING FLOOR EXPERIENCE THE MAXIMUM FLOOR ACCELERATION.

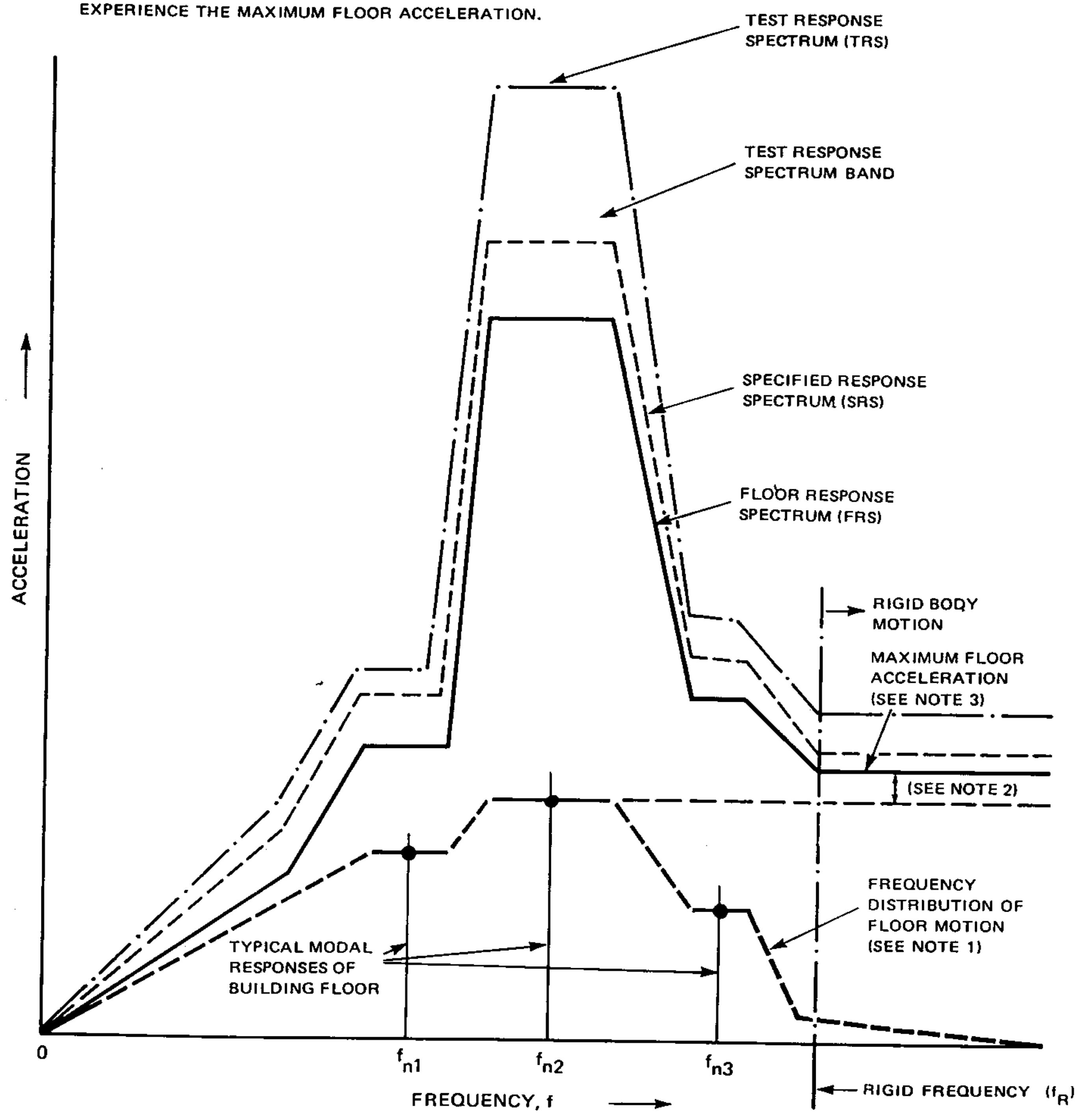


FIGURE 2.1 SEISMIC TERMINOLOGY

Mode Shape (ϕ) means the deformed shape of a system corresponding to its free vibration at one of the natural frequencies of the system.

Module means an assembly of interconnected mechanical and electrical parts constituting an identical device or instrument, which is used with, or as an auxilliary to, other equipment, and is not supported directly from a surface having a defined seismic motion.

Natural Frequency (or Frequencies) means the frequency (or frequencies) at which a body vibrates due to its own physical characteristics and elastic restoring forces, brought into play when the body is distorted in a specific direction and then released, while restrained or supported at specific points.

Octave means the interval between any two frequencies separated by a ratio of two.

Period is the inverse of natural frequency, and is usually stated in seconds.

Predominant Frequency means the vibration frequency at which the maximum response of the structure occurs. It is generally the lowest natural frequency of the structure or component, depending on the direction and/or frequency content of the forcing function.

Proof Testing means vibration testing to a specified vibratory input.

Purchaser means the ultimate customer, the purchaser, or the agent representing him.

Response Spectrum means a graphical display of maximum vibratory response (acceleration, velocity, displacement) versus frequency, for a family of single-degree-of-freedom oscillators having a range of natural frequencies and specified damping, corresponding to a specified motion at the base of the support.

Restraint means a structural element which restricts unwanted degrees of freedom of the equipment.

Rigid Frequency means the frequency at which the FRS approaches the maximum floor acceleration or 33 Hz, whichever is greater (see Figure 2.1).

Note: Rigid equipment for seismic design and seismic qualification refers to equipment whose natural frequency in the 'as mounted' condition is greater than the rigid frequecy.

Seismic Qualification means the verification of seismic adequacy, through testing or analysis (or both), of the structure, component or system to perform its intended function during, and/or following, the designated seismic event, as defined in the user specification.

Seismic Ground Motion Parameters means the peak ground acceleration, peak ground velocity and peak ground displacement of a seismic time-history motion.

Site Design Earthquake (SDE) means an artificial representation of the combined effects in the free-field at the location of the site, of a set of possible earl quakes having occurence rates of 0.01 per year, bas on historical records of actual earthquakes applicable to the site, and expressed in the form of response spe tra or a time-history. However, the peak ground acc eration shall not be less than 0.03 g.

Note: The SDE represents a hypothetical ground moti less severe but more probable than the DBE, and is u ed as the design seismic motion for some systems.

Specified Response Spectrum (SRS) means t response spectrum* required by the purchaser as pa of his specification and constitutes a requirement to be met (see Figure 2.1).

Stiffness (or Spring Constant) means the ratio of an a plied force to the corresponding deflection. It is calculated from the structural properties of the syster and is the inverse of flexibility.

Structure means any load bearing system in a nuclear power plant which is directly supported on the fou dation medium and which houses and/or supports co ponents and equipment.

Support means a structural element which transfers t load from the equipment to the building structure.

System means an assemblage of equipment, components, structures etc., in a nuclear power plant whi is interdependent or connected (or associated) togeth to perform a specific function(s), and viewed as an enti ty for the purpose of analysis or reporting.

Table Motion Spectrum means the required seism test motion (acceleration/frequency plot) at the location of a module mounted on an intermediate support (rac cabinet, console, etc.).

Note: The table motion spectrum is not a response spectrum but the required test motion at the mountir point of the module being tested.

Test Response Spectrum (TRS) means the maximum response of a family of SDOF oscillators, with specifi damping, when subjected to the actual shaker tab motion (see Figure 2.1).

Time-history means a record of the amplitude vibratory motion versus time in terms of any of a celeration, velocity or displacement.

Note: A time-history may be a previously record ground motion or a synthetic time-history represe tative of the ground motion at the site, due to a possible earthquake or a set of possible earthquakes.

* See definition

3. SEISMIC DESIGN PHILOSOPHY

Nuclear power plants licensable in Canada must provide assurance against the release of potentially hazardous quantities of radioactive materials, and assure the integrity of structures and components of the nuclear power plant in the event of an earthquake.

This goal is achieved by following a rational design process, as discussed below.

3.1 Seismic classification

Seismic classification of sufficient structures and components is required to ensure that the function described below can be fulfilled in the event of a DBE at the site:

1) The reactor must be capable of being shut down and of being maintained in that state indefinitely.

2) It must be possible to remove decay heat from the fuel during this shutdown period. (Note: The primary coolant system boundary shall not fail in such a manner as to constitute a loss-of-coolant-accident.)

3) The structures and systems outside the containment area are designed so that any radioactivity releases are within the limits permitted by the siting criteria of the Atomic Energy Control Board.

The seismic classification comprises the design earthquake level and a seismic category. Seismic classification lists for each project define the systems and structures requiring seismic qualification.

3.1.1 Seismic category

The extent to which each structure and system shall remain operational is established by means of seismic categories for individual structures and components of each system. The seismic category defines the following two requirements of the component:

a) The detailed functional requirement, if any, of the component to meet the safety function;

b) The requirement to perform during, after or during-and-after an earthquake.

There are two basic categories:

Category A: Systems which must retain their pressure integrity during and following an earthquake to ensure and maintain the safety-related system operation.

Category B: Systems which must retain their pressure integrity and/or function mechanically and/or electrically, as applicable, during and/or following an earthquake, to ensure and maintain the safety-related system operation.

3.1.2 Design earthquake levels

To provide additional assurance of critical systems performing their safety-related functions in the event of an earthquake, selected safety-related systems in the nuclear power plant are designed to specified earthquake levels as follows:

1) Design Basis Earthquake (DBE)

The Design Basis Earthquake for a plant is defined as an artificial representation of the combined effects in the free-field at the site, of a set of possible earthquakes having a sufficiently low probability of exceedence during the life of the plant, expressed in the form of response spectra or a time-history.

2) Site Design Earthquake (SDE)

The Site Design Earthquake for a plant is defined as the maximum predicted effect in the free-field at the site, having an occurrence rate of 0.01 per year, based on historical records of actual earthquakes applicable to the site, expressed in the form of response spectra or a time-history. The SDE shall have a peak ground motion acceleration not less than 0.03 g.

The DBE and SDE for the plant are specified by at least a peak horizontal ground acceleration value, as well as the design ground response spectrum or time-history. The peak ground acceleration values for the DBE and SDE are determined from a study of site seismicity based on an examination of historical and instrumented earthquake records for the area, as well as the seismotectonics of the surrounding geological structure.

3) National Building Code of Canada (NBCC) earthquake (or equivalent). The NBCC earthquake is defined by the ground acceleration at the site for an earthquake return period of 100 years based only on historical records applicable to the site. The NBCC earthquake criteria are the minimum to be applied to any structure or component where the DBE or SDE are not already specified (see 6.2.2).

3.2 Loss-Of-Coolant Accident consideration

The safety requirements for common-mode incidents in CANDU stations rule out a loss-of-coolant (LOC) accident caused by a DBE because of the small probability of this event. Accordingly, the seismic design does not consider the effects of a LOC accident combined with the effects of a design basis earthquake (DBE). To provide additional assurance of plant safety during and following a DBE, the Emergency Water System is used to provide the make-up for any loss due to small leaks which may occur in the primary heat transport system or in systems not required to be seismically qualified. The containment building is designed for the combined effect of the DBE plus a containment building pressure equal to the dousing-water pressure set point.

3.3 Seismic qualification

Seismic qualification of a system refers to the demonstration of structural integrity and/or the ability of the system to perform its required function during and/or after the applicable design earthquake (DBE or SDE).

Seismic qualification of systems may be achieved by any of the following approaches (see Figure 3.1):

1) Seismic analysis
2) Testing
3) Combination of analysis and testing

The choice of approach for seismic qualification of a particular component or structure depends on the type, size, shape and complexity of the item, as well as availability and scheduling considerations. Documentation showing proof of seismic qualifications must justify the choice of method (see 4.18).

Generally, a seismic analysis approach is adopted when the dynamic behaviour of a system can be adequately modelled. Testing is resorted to when the behaviour of a system cannot be reliably predicted by analysis. Complex components required to maintain their function (e.g. relays, valves, instrumentation, etc.) fall into the latter category. A combination of analysis and testing is recommended where analysis or testing alone does not provide adequate proof of seismic qualification due to the nature of the item, or due to limitations of the facilities, or if added assurance of seismic qualification is required, or where low-level testing is used to establish the dynamic characteristics of the system to aid in the analysis (see 5.3.3).

Seismic qualification may be for a particular application, or it may be intended to cover more than one site condition. In the latter case, the design motion should have sufficient amplitude and frequency content to envelop the various site conditions.

The requirements for seismic qualification by analysis and testing are discussed in Sections 4 and 5, respectively. The design criteria are given in Section 6.

3.4 Seismic loading

The following considerations apply for the purpose of seismic loading, when performing seismic qualification by analytical methods:

1) The applicable design earthquake is treated as an extreme environmental load having a low probability of exceedence.
2) Only one design earthquake as applicable (see 3.1), is assumed to occur during the life of the plant.
3) For components being seismically qualified by analytical methods, seismic loads are combined with other non self-limiting loads (e.g. pressure, gravity, mechanical loads, etc.) as discussed in Section 6, together with a fatigue analysis where indicated.
4) Fatigue analysis of supports and structures is not normally required, as stress levels and cycles are generally sufficiently low.
5) Transient loads which persist for a sufficiently long period or occur frequently, as stated below, are treated as upset loads for the purpose of seismic design of components:
   a) Transient loads lasting 15 minutes or longer and expected to occur on a daily basis.
   b) Transient loads lasting 8 hours or longer and expected to occur once per month.
   c) Transient loads lasting 4 days or longer and expected to occur once per year.

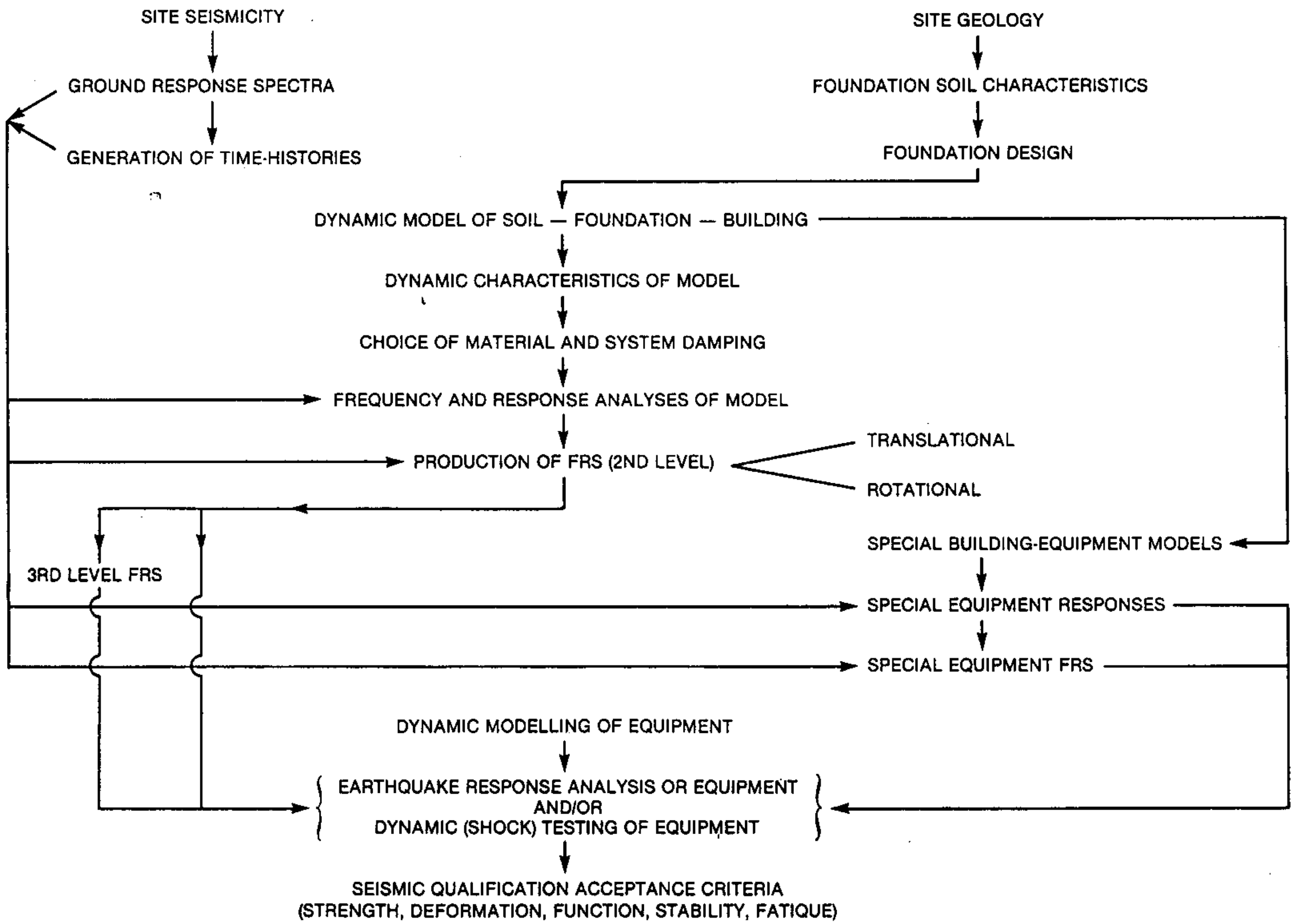


FIGURE 3.1 SEISMIC QUALIFICATION PROCESS

4. REQUIREMENTS FOR SEISMIC QUALIFICATION BY ANALYTICAL METHODS

4.1 General

Seismic analysis is used to predict the dynamic response of a system to a design seismic excitation represented by the applicable design earthquake. The responses commonly sought are: accelerations, displacements, forces, moments, and number of loading cycles.

In performing a seismic analysis, the system is represented by a suitable mathematical model and analyzed using acceptable methods based on rational assumptions and criteria. The results of the response analysis are used to compute seismic stresses. These are combined with stresses resulting from normal or sustained loads, and checked against the allowable stresses* (see Section 6). Figure 4.1 is a logic chart for seismic qualification by analysis.

This report does not exclude or specify any of the available valid methods of earthquake analysis, but provides minimum requirements to be met.

4.2 Method of analysis

4.2.1 General

If analytical methods of seismic qualification are used to ensure that the required functions of safety-related systems and structures are maintained, a dynamic analysis procedure shall be used, except where it can be demonstrated that the use of an equivalent static load method (see 4.2.4) provides adequate conservatism. The commonly accepted methods of dynamic analysis for computing seismic responses of structures or components are the modal superposition method and direct integration method.

If alternative methods are used, these shall be documented and justified with the design analysis.

4.2.2 Modal superposition method

The modal superposition method generally uses the following approaches:

a) Time-history method
b) Response spectrum method

If modal superposition methods are used, all significant modes shall be included in the analysis (see 4.12).

a) Time-history method

In the time-history method, the equations of motion are solved for a large number of time steps, which requires a spectrum-compatible time-history motion as the seismic input. Alternatively, a number of time-histories are applied, one at a time, to determine the worst effects of each. The response of the system is calculated as a function of time after transformation to modal coordinates. The time-history method requires a much larger computational effort than other methods. This method is more flexible than the response spectrum method or the equivalent static load method. In addition to solving linear elastic problems, this method can handle non-linear problems.

b) Response spectrum method

In the response spectrum method, the seismic response (maximum relative displacement, maximum velocity and maximum absolute acceleration) of the system is obtained separately for each independent spatial component of a tri-axial seismic motion. The seismic input is in the form of design ground response spectra (for structures) or floor response spectra (for components). The equations of motion are solved to determine natural (modal) frequencies, modal displacements and modal participation factors of the system for a selected value of modal damping (see Table 4.2), for each seismic input direction.

This method is more general and less conservative than the equivalent static load method, and is used to obtain the dynamic response by damped linear-elastic analyses of complex systems. The most probable maximum value of the system response R of a given element to a given earthquake motion, is obtained as the root-sum-square of individual modal responses as follows:

$$R = \left(\sum_{k=1}^{N} R_k^2 \right)^{1/2} \qquad (4.1)$$

where R_k is the response for the k^{th} mode and N is the number of significant modes considered in the modal response combination.

For closely spaced modes, refer to 4.13.

4.2.3 Direct integration method

This is a time-history method where the response of the system is calculated for a large number of time-steps by transforming the differential equation of motion into a set of algebraic equations involving mass, stiffness and damping matrices.

4.2.4 Equivalent static load method

The equivalent static load method is a quasi-static approach which may be used to evaluate the seismic loads for relatively simple systems. This method of analysis may be used under the following conditions:

a) If the function of the system being analysed is limited to structural integrity, including maintaining a pressure boundary.
b) If the system can be realistically represented by a simple model (maximum 3 degrees of freedom) and the

* Sometimes deflections rather than stresses govern the design.

method produces conservative results in terms of response.

c) If the system does not support another component, unless the supported component is rigid.

d) If the design and analysis for seismic loading accounts for relative motions between all the support points.

e) If results are conservative compared to dynamic analysis methods (from experience).

The equivalent static load, (V_p) representing the effect of seismic loading, is obtained as a lateral load for the appropriate level of component damping, and is distributed according to the mass distribution of the system or is applied at the centre-of-gravity of the system as appropriate, as follows:

a) Where response spectra are available for the support point, the equivalent static load for a supported system or component may be taken as given below for the appropriate damping of the system or component:

$$V_p = 1.5\, W_p A_p \tag{4.2}$$

where V_p = equivalent static force to be applied at center of mass of the system or component,

W_p = weight of system or component including liquid contents,

A_p = peak acceleration from support point response spectrum for the appropriate system or component damping value, in g's.

b) Where response spectra are not available for the support point,

$$V_p = 10.0\, W_p A_f \tag{4.3}$$

where A_f = maximum floor acceleration corresponding to applicable design earthquake (DBE, or SDE) in g's.

c) Where floor accelerations are not available,

$$V_p = 40.0\, W_p A_g \tag{4.4}$$

where A_g = peak value of ground motion corresponding to the applicable design earthquake (DBE or SDE) in g's.

The seismic force distribution on different types of equipment is shown in figure 4.2.

4.3 Mathematical modelling

The mathematical model of a system for dynamic analysis shall adequately represent the dynamic characteristics of the physical system, e.g., mass, stiffness and damping. The commonly used models are the lumped-mass model and the finite-element model:

a) Lumped-mass model

In most instances, the system can be adequately modelled by the use of beam elements, with the masses of the system lumped at node points and the node points joined together by beam elements. Beam theory, accounting for the flexural and shear deformations is used to define the properties of the elements.

b) Finite-element model

In those instances where the complexity of the system is such that it cannot be adequately represented by a lumped-mass model, a finite-element model may be used. The selection of the element type and grid size must be consistent with the assumptions used in the derivation of the elements.

The general criteria for selecting an adequate model are discussed below.

4.3.1 Significant degrees-of-freedom

A sufficient number of node points of degrees-of-freedom shall be considered in the analytical model to adequately determine the response of the system. The number shall be considered adequate when additional degrees-of-freedom do not result in more than a 10 percent change in predominant frequency or a 10 percent increase in response. The nodes should be selected such that they coincide with the concentration of the system mass (i.e. at floor levels or at locations at which there is a continuity in the system stiffness). The distance between the lumped-masses or node points should be selected such that reasonably accurate results relative to an exact solution can be achieved with minimum computational effort. An acceptable upper limit for the distance between node points may be based on the span length of a fixed beam whose fundamental frequency lies between 20 and 30 Hz. For piping systems, the simply supported span length between nodes should have a fundamental frequency above 30 Hz. (See also 4.12, Significant modes.)

4.3.2 Axial, flexural and shear stiffness

The axial and flexural stiffness of the member is accounted for in the lumped-mass model by including the cross sectional area and moment of inertia of the actual system. For flexible, slender systems, the shear deformation is small and its effects on the transverse stiffness can be neglected. In systems where the shear deformation is significant, the shear displacement must be accounted for in the analysis, since it has the effect of reducing the transverse flexural stiffness and the fundamental frequency of the system. Shear stiffness may be neglected if it is equal to or less than 10% of the flexural stiffness. The shear stiffness may be represented in the model by the inclusion of the effective shear area, which is generally less than the cross-sectional area.

4.3.3 Rotational degrees-of-freedom

The rotational degrees-of-freedom may be neglected in the lumped-mass model, where the rotational inertia forces generated in the dynamic analysis are small. Where rotation alters the natural frequencies of the structure or component by more than five percent, the effect of rotational degrees-of-freedom shall be included. This is particularly important for tall components, such as the primary heat transport system boilers, pumps and pressurizers which are pendulum mounted and are free to rotate about their centre of percussion.

4.3.4 Torsional degrees-of-freedom

Torsional degrees-of-freedom may be significant where the centre-of-mass is eccentric to the centre-of-rigidity. Non-symmetrical features of geometric mass and stiffness shall be modelled to include their effect in the analyses. Torsional effects can be neglected for symmetrical systems, and the analysis based on a two-dimensional model. For non-symmetric systems, torsion can be neglected, if the effect of torsion on the natural frequencies of the structure or component considered can be shown to be less than five percent.

4.4 Seismic inputs

Floor response spectra shall be used as seismic inputs for seismic qualifications of equipment. Floor response spectra shall be generated by any of the following accepted methods:

a) Direct generation method using ground response spectra

b) Time-history method

In a), a modal analysis of the building structure is performed to determine its frequencies and mode shapes. Floor response spectra are generated by the use of suitable amplification factors. These amplification factors are determined by a study of the responses of actual earthquake records or by a simulation of earthquake motions by means of an appropriate wave-form which possesses the amplifying characteristics of a real earthquake. Acceptable methods are described in References 3 and 4.

Method b) requires the use of a spectrum-compatible motion. The spectra generated from a time-history should envelop the response spectra at a sufficient number of frequency points. In this method, time-histories of floor motions are generated from a seismic analysis of the building structure (see Reference 5). Floor response spectra are obtained by computing the response spectra of the respective floor motion time-histories.

Other methods can be used, provided they are rational and can be shown to be equivalent to the methods described above.

For the purpose of design, the computed floor response spectra need to be smoothed and broadened to take into account uncertainties in estimating those parameters which affect the frequency of the structure. The peaks shall be broadened by $\pm$ 15 percent, and the valleys shall be bridged similarly.

Alternatively, sensitivity studies shall be undertaken for ranges of various parameters, in which case less than $\pm$ 15 percent broadening may be acceptable.

4.5 Decoupling criteria

In most instances, interaction effects between the primary structure and the supported equipment are negligible. Where the equipment had a relatively small mass and high frequency it is sufficient to include the equipment mass with the mass distribution of the primary structure in the mathematical model. If the component is connected to the structure by flexible connections, e.g., piping supported by hangers, the mass of the component need not be considered with the structural model. There are, however, major items of equipment whose stiffness, mass and resulting frequency range should be represented in the building (structure) model to account for possible dynamic interaction effects. Decoupling criteria are important to decide if the supported system (component) should be included in the model of the supporting system (structure).

Decoupling is acceptable if equations 4.5 and 4.6 below are satisfied (Reference 6):

$$\mu \leq \left(\frac{1.1\theta - 1}{10\theta}\right) \text{for } \theta \geq 1.0 \qquad (4.5)$$

$$\mu \leq \left(\frac{1.1 - \theta}{10\theta}\right) \text{for } \theta \leq 1.0 \qquad (4.6)$$

where:

μ = the ratio of a modal mass of the secondary system to a modal mass of the primary system

f_1 = a modal frequency of the primary system

f_2 = a modal frequency of the secondary system

$$\theta = \left(\frac{f_2}{f_1}\right)^2$$

Modal mass 'm_j' for mode $j = \sum_{r=1}^{N} M_r \phi_{rj}^2$

where:

M = lumped (Modal) mass
ϕ = mode shape
r = mass number (from 1 to N)
j = mode number

The decoupling criteria represented by equations 4.5 and 4.6 are plotted in Figure 4.3.
If the above criteria are not satisfied, a coupled model of the primary and secondary systems should be analyzed.

4.6 Soil - structure interaction

'Soil-structure interaction' refers to the effects of the soil-supporting medium on the motion of the structure. The soil-structure system can be modelled using either a discreet parameter representation (springs and dash-pots) or a finite-element model of the soil. The basic considerations described in 4.3 regarding modelling, also apply to soil-structure interaction.

For the discreet parameter representation, analytical methods based on exact or approximate closed-form solutions for an elastic or viscoelastic half-space (uniform or layered) shall be used to derive impedance functions. Equivalent springs and dashpots are deduced from these impedance functions and incorporated in the model of the structure. The response of the system is obtained from standard methods. Embedment effects are accounted for by modifying the impedance functions. Non-linearities in the soil are accounted for by using equivalent linear properties and by iterating the solution until strain-compatible properties are obtained.

Alternately, the impedance functions may be derived using a finite-element representation for the soil. Using finite-elements for the soil and finite-elements or lumped-masses for the structure, the response of the soil-structure system may be calculated in one step.

4.7 Structure stability

The factor of stability of a structure against either overturning or sliding, during a design basis earthquake, shall not be less than 1.25 using a static method applying the maximum horizontal and vertical forces determined from the dynamic seismic analysis of the structure. For such analyses, the maximum vertical seismic force shall be considered to act upwards and its overturning effect may be combined with that of the maximum horizontal overturning effect, using the square root of the sum of the squares of the two overturning moments.

When the static factor of stability against either overturning or sliding is less than 1.25, a dynamic time-dependent stability analysis shall be undertaken to establish the actual stability at each instant of time. Where such a dynamic analysis shows that liftoff (i.e. separation from the foundation medium) due to an overturning moment exceeds 50% of the base area, a non-linear dynamic analysis shall be applied. Such dynamic-stability analyses shall show that overturning or sliding is avoided. Under such conditions, dynamic failure of th foundation medium shall also be avoided.

Where ground water is a design criterion (buoyancy o setting the restoring moment due to gravity) the buoyan effect (uplift) on the structure shall be applied to th above stability analysis.

4.8 Damping

4.8.1 General

Under seismic loading conditions, the damping effec resulting partly from internal energy dissipation withi the structural material and partly from interface shea (friction) at structural joints and connections, is con veniently represented as equivalent viscous damping Damping is a function of amplitude of motion and of in duced stress levels, and is expressed in terms of percen tage of critical damping.

Recommended values of damping are tabulated i Table 4.2. Where response analysis using these dampin values indicates that higher damping values are justifie increased damping may be applied. When higher damp ing values are used, they shall be verified by actual tes results taken from similar structural systems, usin similar methods and materials of construction and com parable excitation and final response levels.

Damping ratios for soils shall take into account th stress-strain properties corresponding to the level o seismic ground motion and the effect of radiation damp ing. Appropriate laboratory tests shall be used to dete mine damping ratios for soils. In the absence of ap propriate test or analysis results, acceptable dampin values for two types of soil are presented in Table 4.2.

4.8.2 Composite damping evaluation

A nuclear power plant is a complex combination of struc tures and components with different damping characte istics, with considerable variation in damping througho the system. Thus, an equivalent damping value must b determined for each mode of vibration. Either the com posite modal damping approach or the modal-synthesi technique may be used to account for element-asso ciated damping.

In the composite modal damping approach, dampin associated with each mode is determined by means of weighting function which can be based on either th strain energy or the kinetic energy of the system. (Th strain energy method is preferred).

Using the strain energy approach, the composit modal damping ration of the j^{th} mode (B_j) can be e pressed as:

$$B_j = \frac{\sum_{i=1}^{N} (\phi)^T b_i \; [K_i] \; (\phi)}{(\phi)^T \; [K] \; (\phi)} \qquad (4.$$

From the kinetic energy approach, this expression is given by:

$$B_j = \frac{\sum_{i=1}^{N} (\phi)^T b_i \, [M_i] \, (\phi)}{(\phi)^T \, [M] \, (\phi)} \qquad (4.8)$$

where:

$[K]$, $[M]$	=	assembled stiffness matrix and mass matrix, respectively
$[K_i)$, $[M_i]$	=	stiffness matrix and mass matrix, respectively, associated with the i_{th} element
(ϕ)	=	j^{th} normalized modal vector
$(\phi)^T$	=	j^{th} transposed normalized vector
b_i	=	damping ratio associated with element i
N	=	total number of degrees-of-freedom

For models which take into account the effects of soil-structure interaction by the lumped mass/soil-spring approach, the method defined by equation (4.7) is acceptable. For fixed base models, either equations (4.7) or (4.8) may be used.

Other techniques based on modal analysis, described below, have been developed and are particularly useful when more detailed data on damping characteristics of structural elements is available. The modal-synthesis approach is based on achieving displacement compatibility and force equilibrium at the system interfaces, and utilizes element eigen-vectors as internal generalized coordinates. It consists of the following:

1) Extract sufficient modes from the structural model.
2) Extract sufficient modes from the finite-element model of the soil.
3) Perform a coupled analysis using the modal-synthesis technique, and using the data obtained in steps (1) and (2), with appropriate damping ratios selected for structures and soil elements.

4.9 Earthquake occurrence and duration

The analysis of structures and components for seismic fatigue effects shall be based on the dynamic response resulting from the occurrence of only one SDE or DBE, as applicable, during the operating lifetime of the nuclear power plant as described in 4.15.

The duration of earthquake for time-history analyses shall be the most severe 10 seconds of the design basis time-history, applied to the base of the primary system, for seismic response analysis and 15 seconds for seismic fatigue analysis.

4.10 Hydrodynamic effects

When a vessel containing fluid is accelerated, a certain portion of the fluid acts as if it were a solid mass in rigid contact with the walls. The acceleration also induces oscillations of the fluid, which contributes to further dynamic pressures on the walls. If a vessel is submerged in a fluid, the 'attached mass' or 'virtual mass' effect applies. For a circular component, e.g., a cylinder or pipe, vibrating in the transverse direction, the 'attached mass' is equal to the mass of the volume of fluid displaced.

The dynamic effects of fluids contained in, and surrounding a component shall be taken into account, including their effect on the supporting structures. Methods of computing these effects are described in References 7 and 8.

4.11 Combination of triaxial seismic motion

Depending on the method of dynamic analysis adopted, i.e., response spectra or time-history, the following two approaches are acceptable for combining three-dimensional earthquake effects:

a) Response spectrum method

In the response spectrum method of dynamic analysis, the maximum system response due to each of the three components of earthquake motion shall be combined by taking the RSS of the maximum co-directional response caused by each of the three components of input motion at a particular point of the system or of the mathematical model.

b) Time-history method

In the time-history approach, the following methods for combining responses shall be adopted:

i) When maximum responses due to each of the three components of input motion are calculated separately, the method for combining three-dimensional effects is identical to that described in (a), except that the maximum responses are calculated using the time-history method instead of the spectrum method.

ii) When time-history responses from each of the three components of input motion are calculated by the time-step method and combined algebraically at each time-step, the maximum response is obtained from the combined time solution.

4.12 Significant modes

The effect of all significant modes shall be considered by including a sufficient number of modes in the analysis. In general, there will be as many modes as there are degrees-of-freedom. To avoid an excessive number of modes, it is not necessary to consider modes having frequencies above 33 Hz.

A satisfactory check for sufficiency is to add the 'residual' modes* to the number of modes being considered. If this addition does not result in more than a 10% increase in response, then the inclusion of additional modes is unnecessary.

4.13 Closely spaced modes **

In a response spectrum modal dynamic analysis, if the modes are closely spaced, the methods given below are recommended for obtaining the maximum representative value of response of a given element of the system which is subjected to a single independent spatial component of a three-component earthquake.

a) Closely spaced modes should be divided into groups that include all modes whose frequencies are within 10 percent of each other. The responses of these groups are combined by the absolute sum method, and combined with the remaining modal responses using the square root of the sum of the squares rule.

b) The most probable maximum value of a particular response of a given element to a given component of an earthquake, R, is given by:

$$R = \left(\sum_{k=1}^{N} R_k^2 + 2\sum |R_i R_j| \right)^{1/2}, \; i \neq j \qquad (4.9)$$

where R_k and N are as defined in 4.2.2, and the second summation is to be done on all i and j modes whose frequencies are closely spaced to each other. If ω_i and ω_j are the frequencies of the i^{th} and j^{th} modes, respectively, the following equation applies:

$$\frac{\omega_j - \omega_i}{\omega_i} \leq 0.1 \qquad (4.10)$$

and $1 \leq i \leq j \leq N$

4.14 Multiple-support excitation

Often components are supported at several points on the same structure or on different structures, and the support points have different seismic motions characterized by different floor response spectra. In addition, the supports may undergo differential movements, leading to additional stresses on the component being supported. Seismic analysis of such components must consider i) the inertial effect, and ii) the differential support movement effect.

* The 'residual modes' can be represented by a single rigid-body mode.

** Two consecutive, codirectional modes are defined as closely spaced if their frequencies differ from each other by 10 percent or less of the lower frequency.

a) Response spectrum method

In the response spectrum method of analysis, the inertial effect shall be taken into account by either the single or the multiple response spectrum method, as follows:

In the single response spectrum method, an envelope of the floor response spectra of all the supports is used as the common seismic input at all supports. If the spectra for one support differ greatly from the others, this method gives very conservative results for locations close to the support(s) with the lower input(s). In such cases, the multiple response spectrum method gives more realistic results.

In the multiple response spectrum method dynamic alanysis is performed by applying the appropriate response spectra at one support at a time with no motion applied to the other aspects. By repeating the process at each support, the total response of the system can be determined as detailed below. This method is based on the concept of influence coefficients used in structural mechanics. Refer to Appendix A for an explanation of this method.

Combination of individual responses at each support shall be based on the ABS method where the seismic inputs are known to be in phase. Otherwise combination of responses shall be by the RSS method.

In the response-spectrum method, the differential support movements are introduced as static displacements, and their effects are combined with the inertial effects by the absolute sum method. The differential support movement is conservatively estimated from the floor response spectrum as follows; The maximum displacement of each support is predicted by $S_d = S_a/\omega^2$, where S_a is the acceleration at the rigid frequency, and ω is the fundamental frequency of the support structure in radians per second. The support displacements should be imposed on the component in the most unfavourable manner. This method gives very conservative results where a large part of the movement results from in-phase motion (e.g. when the structure has predominantly soil-interaction modes causing rigid-body motions). In such situations, a more realistic design is obtained by separating the in-phase movements from the total movements, and combining only the out-of-phase movements in the most unfavourable way. The methods of combining in-phase and out-of-phase movements are given in Appendix A.

b) Time-history method

In the time-history method, the seismic inputs at each of the support points are the appropriate time-history accelerations and displacements. The phase relationships of input motions are taken into account at each step, so that the results are less severe and more realistic than the response spectrum method. The method, however, requires a higher computational effort than other methods.

4.15 Seismic fatigue analysis

Where a seismic fatigue analysis of components and supports is required as indicated in Tables 6.2, 6.3, 6.5, and 6.6, it shall be performed in accordance with the following:

With the application of Level 'C' Service Stress limits for seismic analyses, there is no specific ASME Code (Reference 5) provision for shakedown, ratchetting or fatigue. However, in order to ensure no failures due to an earthquake of an intensity as high as the DBE, seismic fatigue effects shall be evaluated as follows:

a) If the conditions of Paragraph NB-3222.4(d) (Reference 5) or equivalent are met with seismic loads acting together with all other applicable loads, a fatigue analysis is not required.

b) If the conditions of Paragraph NB-3222.4(d) (Reference 5) or equivalent, cannot be met, then Paragraph NB-3228.1(b), or equivalent, shall be applied for performing an elastic seismic fatigue analysis.

c) If the conditions of both Paragraphs NB-3222.4(d) and NB-3228.1(b) or equivalent, cannot be met, then Paragraph NB-3228.3 or equivalent may be applied for performing a simplified elastic-plastic seismic fatigue analysis. In this case, the strain-range under seismic conditions is converted into an equivalent elastic stress for determining the earthquake fatigue effect. Alternatively, the provisions of ASME Code Case N-196 (Reference 9) may be applied. (See Reference 10 for background information).

The duration and occurence of earthquakes for fatigue analysis shall be based on 4.9.

The maximum range of peak stress for fatigue analysis purposes shall be that due to the maximum combined modal response from seismic effects alone, considering the effects of both inertial response and earthquake-induced anchor point movements (where applicable), with the cycles determined as follows:

The minimum number of cycles for a fatigue analysis shall be based on either of the values in rows 1 and 2 of Table 4.1 for the respective primary (ground supported) or secondary (floor supported) system.

Alternatively, a rigorous time-history analysis shall be performed to obtain the response of the system. The integrated fatigue effect on the system shall be based on the appropriate earthquake duration given in 4.9.

The fatigue "usage factor" (i.e. ratio of fatigue cycles applied to cycles permitted at a given alternating stress amplitude) for the appropriate level of design earthquake (DBE or SDE), must be combined with the usage factors derived for all other design conditions involving alternating stresses. Normally, this combination should not exceed unity.

However, as discussed in Reference 11 it is possible to justify a combined usage factor exceeding unity under special circumstances when earthquake fatigue effects are included, provided that the sum of the usage factors does not exceed unity without the earthquake.

4.16 Non-linear analysis

When stresses in the structures are higher than the elastic limit of the material, or for other reasons (fretting, gaps, etc.), the stiffness matrix may be dependent on the amplitude of response. In such cases, the behaviour becomes non-linear.

For sufficiently weak non-linearities, the main effect is an increase in energy losses, which can be accounted for by using larger damping coefficients. Equivalent linear analysis with adjusted parameters can be used in such cases.

For higher non-linearities it will be necessary to modify the stiffness and perform non-linear analysis.

4.17 Computer programs

Standard computer programs used to perform a dynamic analysis should be judged for suitability and capability. The following should be considered in selecting a computer program:

- Simplicity of application
- Suitability of Input/Output format
- Ease of using applicable code formulae
- Ease of introducing system modifications
- Modelling capabilities and restrictions
- Separation of data for two horizontal and vertical responses in the different modes
- Reorganizing operations to be performed by the designer subsequent to a computer run
- Modal combinations
- Application of multiple inputs

Programs other than standard programs may be used, provided they are checked for accuracy by comparing results against a standard program. All computer programs which are used in the analysis, must be documented.

4.18 Seismic qualification report

Seismic qualification reports are required for all components and structures requiring seismic qualification. This report shall demonstrate that the item to be qualified meets its pressure integrity and/or structural integrity and/or performance requirements as stated in the user specification, when subjected to the appropriate design seismic motion.

All qualification reports shall include the following: seismic requirements for the item (per the user specification); justification for the qualifications method adopted (analysis, testing, or a combination of analysis and testing), the seismic loading considered in the qualification and how it was obtained and applied; results and conclusion; approving signature; and date. Qualification reports shall be submitted to the appropriate authority for review and acceptability, as called for in the user specification.

For those safety-related components and structures where a stress report is required, a detailed seismic qualification report must be submitted. This report shall include the following in addition to the content stated above:

- Statement of objective(s)
- Method of analysis and reason for choice
- Full description and justification for the mathematical model selected
- Analysis presented in a form which is readil auditable, by a person qualified in the field of work
- Description of computer programs used and documentation establishing their validity and applicability to the analysis
- Listing of potential failure modes considered in the analysis
- Reference to applicable codes, standards, technical papers, etc.

TABLE 4.1 RECOMMENDED CYCLES FOR FATIGUE ANALYSIS*

	Ground-supported (Primary) Systems	Floor-supported (Secondary) Systems	Remarks
Cycles of response	15 cycles	25 cycles**	Cycles to be applied at the max. combined modal response level, without regard to frequency
Duration of response	5 seconds	8 seconds***	Response to be determined, based on the frequency of the dominant mode, using the maximum combined moda response level.

* Recommendations based on investigations reported in Reference 11.

** For anchor-point movements, use 15 cycles.

*** For anchor-point movements use 5 seconds.

Inertial and anchor-point movement fatigue effects may be taken together by combining the maximum responses due to each effect, using the higher of the primary or secondary dominant modal frequency for 8 seconds duration, or 25 cycles of combined response, whichever is more favourable.

TABLE 4.2 RECOMMENDED DAMPING VALUES (β)*

No.	DESCRIPTION	DAMPING (β)* See Note (c)
1	Large diameter, welded-steel pressure vessels or piping 20 inches (50 cm) in diameter or greater	4
2	Piping greater than 12 inches (30 cm) and less than 20 inches (50 cm) in diameter	3
3	Piping between 6 inches (15 cm) and 12 inches (30 cm) in diameter	2
4	Small diameter piping, tubing and conduit under 6 inches (15 cm)	
	• Clamped supports	1
	• Free supports at close intervals allowing rattling	2
5	Welded steel structures	3
6	Rigid components (welded or cast steel), e.g. pumps and valves, motors, etc.	2
7	Bolted steel structures, e.g. motor control centres, cable pans, switchgear, etc.	5
8	Prestressed concrete structures, e.g. containment	3
9	Reinforced concrete structures	5
10	Soft soil (sediment) — see notes a) and b)	10
11	Competent rock (Granite)	4

* (β = percent of critical damping)

NOTES:

a) For relatively rigid structures located on soft soils or on poor quality rock, higher damping values may be used to take into account radiation damping.

b) Total soil damping values including both material and radiation damping shall not exceed the following (see also Note a):

Horizontal or vertical motions:	30 percent
Rocking motion:	20 percent

c) High damping values may be used, provided they can be fully justified by experiment, or if they are based on actual measurements taken from comparable structures or components subjected to equivalent vibratory conditions, or if response-dependent damping values are determined analytically.

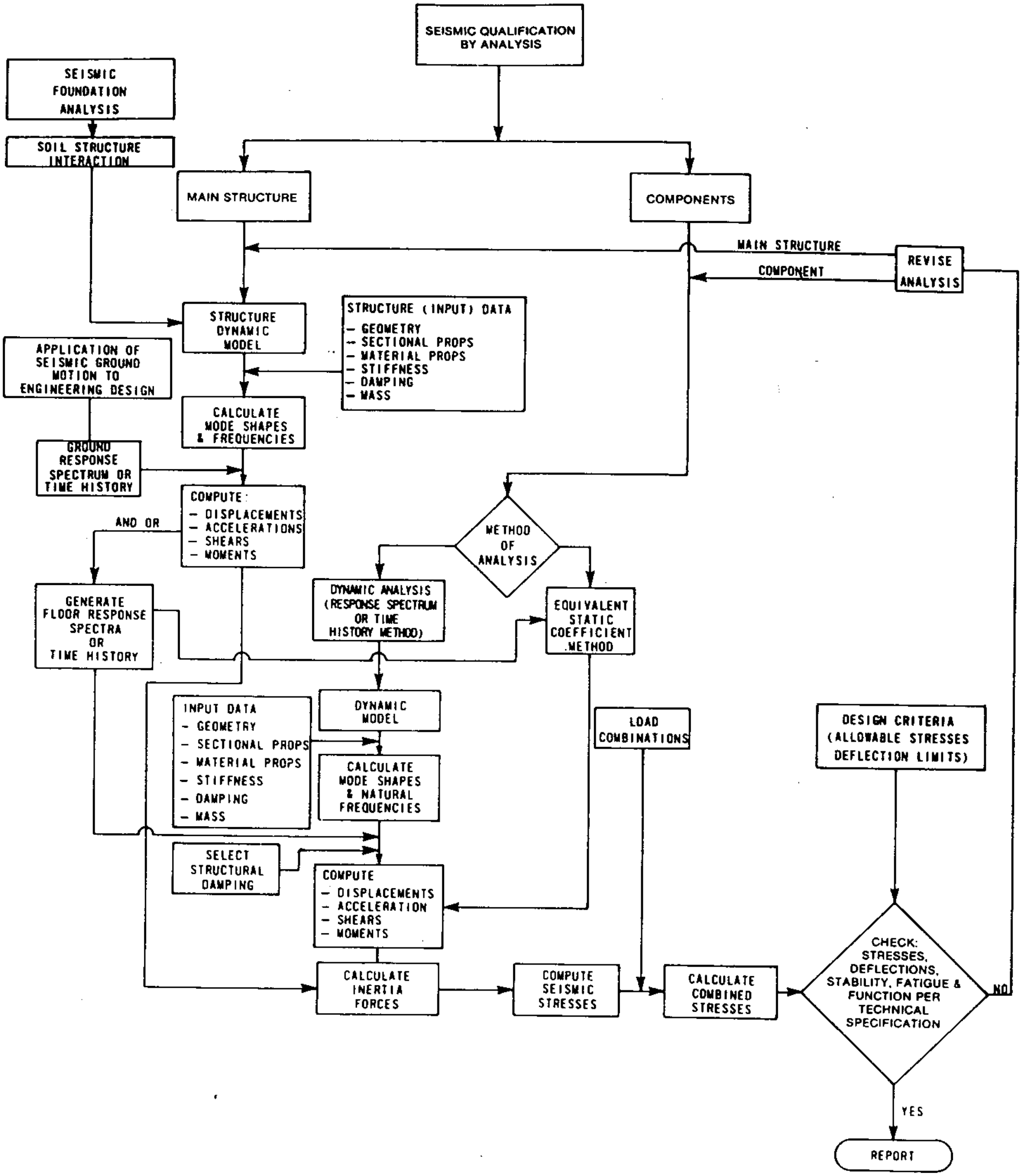


FIGURE 4.1 FLOW CHART OF SEISMIC QUALIFICATION BY ANALYSIS

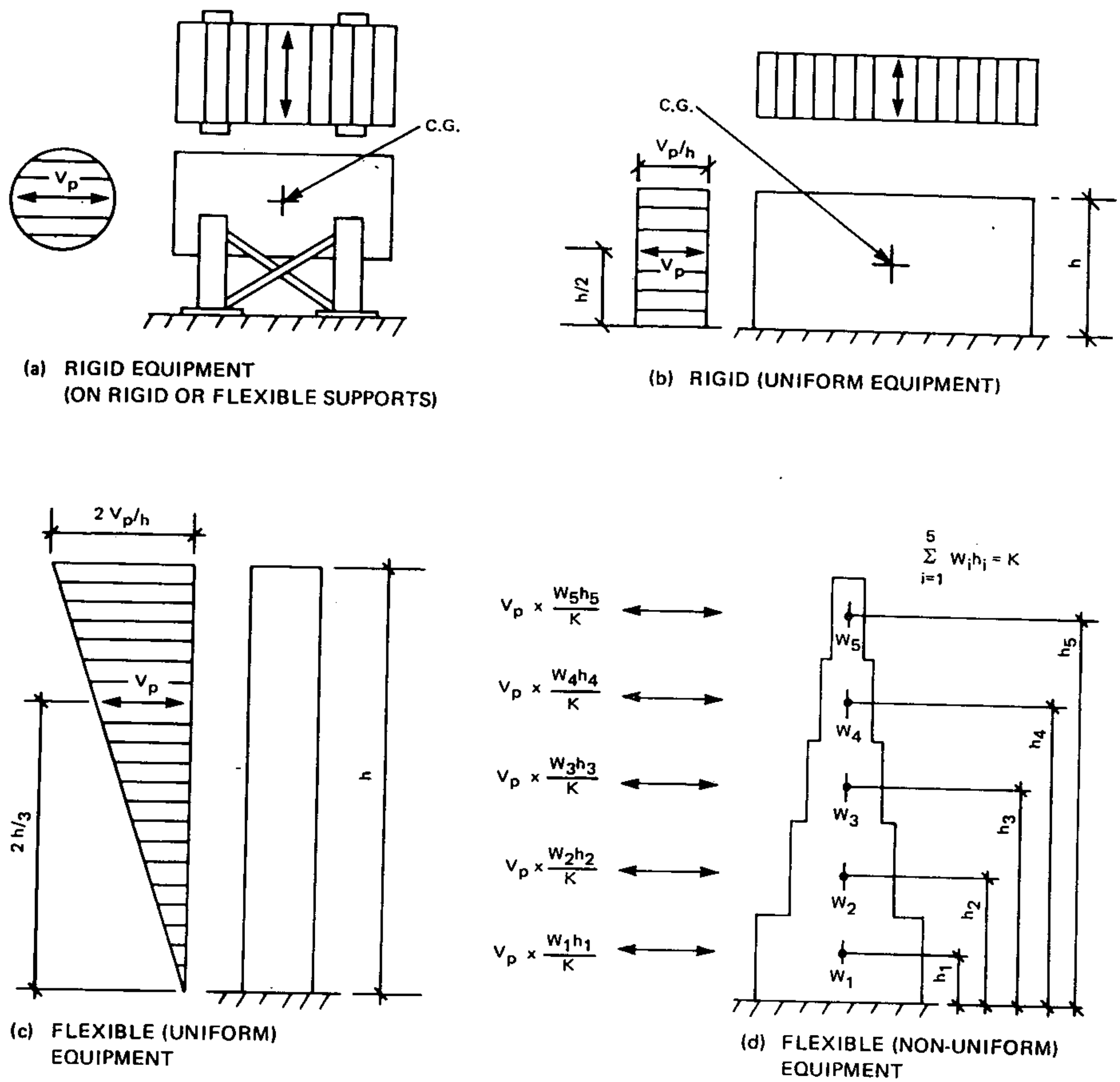


FIGURE 4.2 EXAMPLES OF SEISMIC FORCE DISTRIBUTION ON DIFFERENT TYPES OF EQUIPMENT

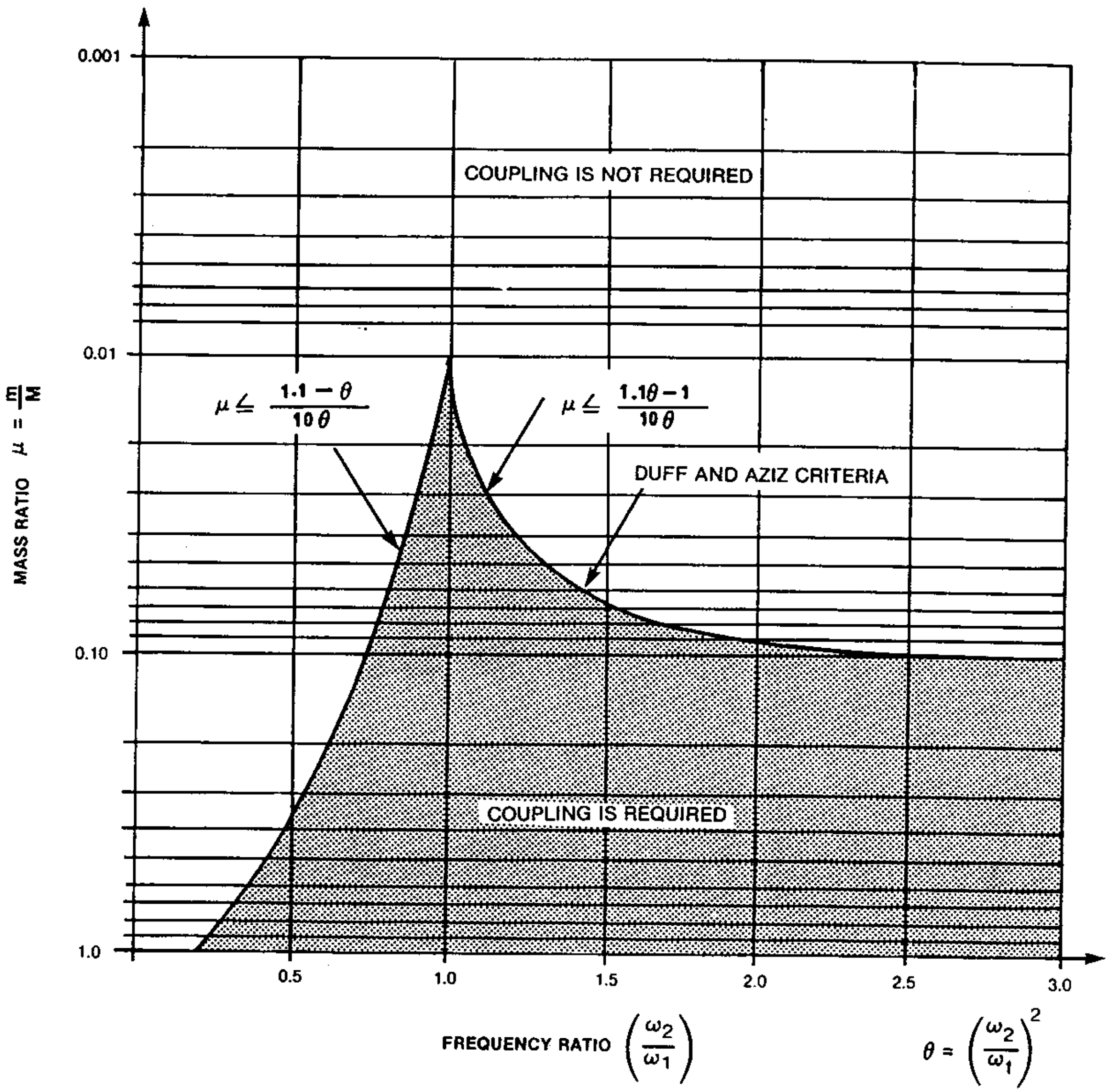


FIGURE 4.3 DECOUPLING CRITERIA

5. REQUIREMENTS FOR SEISMIC QUALIFICATION BY TESTING

5.1 General

When an analysis of the functional capability of equipment cannot be performed with a reasonable degree of confidence, dynamic testing is required to supply such proof. These tests are to be performed on the equipment to be supplied or on a prototype. Full-scale models or reduced-scale models may be used, if necessary. The test shall demonstrate the structural integrity of the component, as well as the ability of the component to perform its intended function during and/or after the design earthquake for which it is qualified, as required. Testing may also be used to check or validate calculations or analytical models.

A meaningful seismic qualification test requires:

a) The equipment under test is subjected to a vibratory motion that conservatively simulates the effect of the design earthquake at the mounting point.

b) The operating environment is simulated correctly as called for in the applicable technical specification. The operating environment implies mechanical loading, pressure, temperature, voltage, current etc., as applicable.

Testing may be performed for a specific application to a specified requirement (proof testing), or it may be to cover many applications (fragility testing). A proof test is a "go, no-go" type of test in which the specimen is subjected to a simulation of the one environment to which it must be qualified. In a fragility test, the specimen is subjected to gradually increasing levels of shaking until it ceases to maintain its structural integrity or its desired critical parameters, i.e., there is a malfunction or an out-of-tolerance operation. The method of testing required to qualify components for any application is dependent on the nature and dynamic characteristics of the equipment and the seismic environment to be simulated.

Full-scale testing may be performed in a test laboratory with a shake table or other suitable device, or may be performed in-situ during construction or prior to start-up. Usually, in-situ tests permit low levels of excitation with only natural frequencies and possible mode shapes to be checked for systems showing linear behaviour.

Equipment similar to that which has been qualified to the same or higher seismic environment need not be re-tested. However, the effects of modifications or variations should be considered. This does not cover modifications following failure of a proof test, which must be confirmed by re-testing. A logic chart for seismic qualification by testing is shown in Figure 5.1.

5.2 Simulation of seismic motion

5.2.1 Mounting*

The flexibility of the support system may significantly modify the dynamic behaviour of the equipment. The following points should be considered for dynamic testing:

a) The component to be tested is to be mounted on the shake table in a manner that duplicates or simulates the intended service mounting. It is acceptable to mount the equipment in other than the in-service mounting condition, if the effect of this difference on the motion is accounted for in the shake table motion.

b) The effect of attachments, electrical connections, pipes, fuel and sensing lines, etc., shall be considered.

c) The orientation of the component during the test shall be the only orientation for which the component is considered qualified, unless justification exists for extending the qualification to an untested orientation. The test shall be repeated for other orientations if the seismic motion is relevant to more than one direction.

d) The orientation and method of mounting the components to the shake table shall be documented in the test report. The effects of fixture or connections used for mounting on the shake table must be evaluated if different from the actual in-service mountings.

e) To obtain increased component motion, particularly at low frequencies where the shake table may have inadequate stroke, the component may be mounted on resilient mounts (motion amplifiers). Such mounts can be selected to have a range of spring rates and damping values to cover the required range of frequencies and component responses where the shake table is deficient. The response should equal or exceed the FRS for which the component is being qualified.

5.2.2 Monitoring

Sufficient monitoring equipment should be used to evaluate the performance of the component before, during, and after the test, as specified. Also, sufficient vibration monitoring equipment should be used to determine the vibration level of the shake table, the response at the mounting location and the response of the component at all critical locations, where specified.

* Mounting refers to all substructures, supports, anchors, etc., between the point of mounting on the floor (elevation) at which the seismic motion is defined, and the actual equipment.

5.2.3 Exploratory testing

Exploratory tests should be run on the equipment to assess the dynamic characteristics of the equipment at a safe test level in order to select an appropriate full-level test without risk of over or undertesting. The exploratory test may be run as a low-level, continuous, sinusoidal sweep at a rate no greater than 2 octaves/minute over the designated frequency range. All resonances are to be recorded.

Resonant responses at high acceleration levels may differ in frequency and damping from that at low levels because of nonlinearities. Also, full resonant response may not be excited at low levels, particulary in the higher modes. Therefore, a low-level exploratory test may not be conclusive as an indication of either equipment dynamic response or lack of resonances.

In the case of equipment with internal moving parts (e.g., engines, motors, compressors, pumps etc.), a low-level exploratory test may not necessarily excite all resonances or provide information about internal resonances, if these are not monitored. For such components, testing at intermediate frequencies by one of the test methods given in 5.3 is required.

5.2.4 Loading

Where specified in the technical specification, seismic qualification tests are to be performed with the components subjected to real or simulated normal operational loads (electrical loads, mechanical loads, thermal loads, pressure, etc.). If the loads are simulated, they must be shown to be equal to or greater than the specified loading.

5.2.5 Module (or device) testing

Modules and devices intended to be mounted on intermediate supports, e.g., panels, rack, console, cabinet etc., should be tested with its intermediate support (see 5.2.1). Alternatively, the response at the module location should be obtained either by direct measurement (at the device location in testing the support), or by a time-history analysis, or by determining the transfer function from the mounting point of the support to the mounting point of the module, and a test response spectrum is generated to qualify the modules separately.

When the mounting is not known, the seismic environment for the modules or devices may be specified by means of a table motion spectrum (see 5.2.7) and the devices qualified by a sine sweep test.

5.2.6 Assembly testing

Large, complex equipment such as control panels comprised of a panel (or frame) may be tested to simulate operating conditions and monitored for proper functional performance. Where it is not practical to simulate all systems simultaneously (e.g., where control panels contain parts of many systems), it is acceptable to such equipment in an inoperative mode with the ac or simulated devices installed. The test should de mine vibration response at the device location (or lo tions) by either direct measurement at full excitatior by determining the transfer function from the assen mounting points to the device mounting points.

5.2.7 Test input motion

The seismic environment to be simulated may be spe fied as a response spectrum, a time-history or a pov spectral density function.

The test input motion shall comply with the followi

a) If the system has one or more mechanical re nances in the frequency range of interest, the sha table motion must produce a test response spectru (TRS) which matches or exceeds all, or the applicat portion of the SRS, using single or multiple freque cy input, as applicable (see 5.3).

b) The TRS must be produced using justifiable ana ical techniques or spectrum analysis equipment.

c) The peak shake table amplitude must be equal to greater than the applicable floor acceleration obtai ed from the SRS, except at frequencies where tl response spectral amplitude decreases below th value.

d) Possible multi-mode and multi-axis seismic effec shall be considered in obtaining the speci response spectrum by modifying the given spectru with suitable factors (see Table 5.1). Lower facto may be used if justified.

e) Overtesting shall be limited as per 5.2.9.

For small equipment mounted on intermediate su ports the test motion may be specified as a table m tion spectrum (see definition).

5.2.8 Duration of testing

A meaningful seismic qualification proof test requir that peak equipment response is produced reliably a for a sufficient number of cycles, and that the durati of the test at least equals the effect of the stror motion portion of the design basis earthquake for t station.

In multi-frequency testing, the test motion shall ha a minimum duration of 15 seconds. In single-frequer testing, the requirement is to test for a minimum of cycles or 25 cycles at each test frequency, as plicable (see Table 4.1). See also 5.2.9.

5.2.9 Overtesting

Overtesting of customer equipment slated for field stallation is a genuine concern from the point of view fatigue as well as hidden damage, e.g., galling, scuffing, fretting, impaction, damage to bearings, cracks in areas of high stress concentration, insulation damage, etc..

Prevention of overtesting shall be a factor in selecting the upper limits of the test response spectrum. Whereas, a high TRS is desirable from the point of view of finding the safety margins in the equipment, it is not desirable if the tested equipment is going to be put into service, because of the possibility of damage of a reduction in cyclic life due to fatigue. Thus, the TRS should not exceed 2 x SRS unless approved prior to the test. The test must therefore, be closely monitored to prevent overtesting.

To prevent overtesting of equipment to be field-installed, the duration of testing shall be limited as follows:

In single-frequency testing the test motion shall not be greater than 5 or 8 seconds at each frequency, provided that a minimum of 15 cycles or 25 cycles have been applied at each selected frequency, as applicable (see Table 4.1). In multi-frequency testing, the test motion shall not be greater than 30 seconds in each direction, nor less than 15 seconds.

5.2.10 Multi-axis and multi-frequency coupling effects

Seismic ground motion is random in nature and is characterized by statistically independent horizontal and vertical components. An acceptable seismic qualification requires that the postulated seismic environment be reproduced in a conservative manner. This requires that the seismic test motion simulate or account for any coupling effects which could result from the multi-frequency, multi-directional nature of the postulated seismic environment. Table 5.1 gives correction factors to account for these effects, depending on the frequency content and the directional nature of the test motion. The given seismic environment (response spectrum or table motion spectrum) shall be multiplied by the factor selected from Table 5.1, unless it can be justified that coupling effects are insignificant.

5.3 Methods of testing

The following methods of testing can be used for seismic qualification of components:

a) Single frequency testing
b) Multiple frequency testing
c) Verification testing

Each of these methods is based on using different waveforms and durations. The selected waveform and duration for any test must simulate the seismic environment at the mounting location.

The choice of test methods depends on a number of factors such as size, nature, complexity, and functional requirements under test, the nature and level of the postulated seismic motion at the mounting, the capability of available test facilities, scheduling; etc.

5.3.1 Single frequency testing

When seismic ground motion has been filtered due to a predominant structural mode, the resulting floor motion may consist of one predominant frequency. In this case, a short-duration, steady-state vibration can be a conservative input excitation to the shake table. Single frequency tests may also be used to determine the resonant modes and damping of the component, provided the excitation level is sufficiently low to avoid over-response due to an excessive amplification factor (see Figure 5.2).

Single frequency tests may be used to fully test components, if it can be shown that the component has no resonances, or only one resonance, or the resonances are widely spaced and non-interacting, or if it can be otherwise justified. Otherwise, the appropriate factors of Table 5.1 shall be used to account for possible multi-modal response deficiencies.

In single frequency testing, test frequencies must be spaced no more than 1/2 octave intervals apart in the required frequency range, unless otherwise justified. Where all resonances to 33 Hz have been positively identified by testing, the single frequency TRS need envelope the SRS only at the equipment resonances with single-frequency input at each resonant frequency.

The commonly used single-frequency methods are shown in Figure 5.1 and described here briefly.

5.3.1.1 Continuous sine testing

In a continuous sine test, the input waveform comprises a number of continuous sinusoidal oscillations on one frequency and the required peak accelerations, applied for a certain duration. Where no resonances exist up to the rigid frequency, the full table acceleration may be applied at any frequency in the test range.

5.3.1.2 Sine beat testing

The sine-beat input test motion consists of a series of amplitude-modulated sinusoids complying with the requirements of 5.2. As used here, the amplitude of the sinusoids represent acceleration and the modulated frequency represents the frequency of seismic excitation.

The series of beats can represent low-cycle effects, with sufficient pause between beats to ensure that no significant superposition of response occurs. A sine-beat vibration input of 5 cycles/beat at each measured equipment natural frequency is considered conservative (see Figure 5.2).

The degree of conservatism in the test increases as the number of cycles per beat increases. Peak beat amplitudes shall be at least equal to the maximum floor acceleration of the specified response spectrum except at very low frequencies, i.e., below the frequency of peak acceleration of the SRS, where values of the SRS shall be met.

5.3.1.3 Decaying sine test

In this test, input to the shake table is in the form of decaying sinusoids with peak amplitude and decay rate of the shake table motion producing a TRS to meet the requirements of 5.2. Figure 5.3 shows amplification factors for various equipment damping levels (here β_e) against damping rate of the applied sinusoid (here β_t).

A series of decaying sinusoids can be used to represent low-cycle effects such that no significant superposition of equipment motion results. The degree of conservatism increases as the decay rate decreases.

5.3.1.4 Sine sweep test

In this test, the input motion is a sinusoidal input with continuously varying frequencies within the frequency range of interest. This test closely approaches the conservatism of the continuous sine test in terms of producing maximum response. The percentage of steady-state resonant response obtained depends on the sweep rate and damping of the equipment. For sweep rates of 2 octaves per minutes or less, and for typical equipment damping, the response exceeds 90 percent. Maximum response is obtained separately at every frequency in the test range. This test is commonly used as a low-level exploratory test. By applying a reduced table acceleration level, a slow sine-sweep can be used for proof testing equipment.

A sweep rate sufficient to excite the responses adequately shall be applied. The recommended sweep rate is as follows:

1 Hz to 4 Hz:	1 Hz/minute
4 Hz to 33 Hz:	$f^2/1000$ Hz/second

5.3.2 Multi-frequency testing

Multi-frequency test methods provide a broadband test motion that can made to closely simulate seismic ground motion. Multi-frequency testing is particularily suited to seismic qualification testing because it results in simultaneous response from all modes of a multi degree-of-freedom system. It is recommended for use in those cases where the seismic motion has not been strongly filtered (e.g. ground-level floors) so that the floor response retains the broadband characteristics. Some of the commonly used multi-frequency waveforms are shown in Figure 5.1 and described here briefly. Input waveforms not specifically referenced here may be used, provided they meet the requirements stated above.

Multi-frequency test input motion must satisfy the requirements of 5.2

5.3.2.1 Time-history testing

A time-history test uses a time-history as the input e citation. Seismic testing may be performed either to given time-history or to one or more time-histories th simulate the probable input to the equipment. A tim history record can be synthesized to match the RRS u ing simulation techniques or the specified time-histor may be used in the test (Reference 16). 5

5.3.2.2 Random motion test

A random motion test uses a vibratory input derive from a random signal source. Filters, amplifiers an other instruments are used to shape the input. A ran dom excitation with amplitude controlled by 1/3 octav (or narrower) frequency bandwidth filters is commonl used. The resulting table motion is analyzed by a spec trum analyzer for the desired damping value and plotte at 1/3 octave (or narrower) frequency intervals over th frequency range of interest.

5.3.2.3 Random motion with sine beat test

To meet a SRS displaying a moderately high peak ma require an unreasonably high amplitude from the ran dom excitation. It is acceptable to adjust the random in put to produce responses to equal or exceed as much of the SRS as possible without using peak input ac celeration substantially greater than the design floo acceleration to achieve this. A sine beat (or beats) is usually superimposed on the random input motion to provide a composite excitation, so that the TRS equa or exceeds the SRS over the desired frequency range The optimum number of oscillations per beat should be determined.

When more than one frequency of sine beats is require to meet the bandwidth of a spectrum, the beats shoul be initiated simultaneously. If the bandwidth of th peak value of the FRS has been widened to account fo uncertainties in building frequency analysis, the beat may be applied in sequence.

5.3.2.4 Complex wave test

When the TRS from random motion cannot be made t fit the SRS within a reasonable tolerance or without e cessive conservatism, a complex wave test may be use The equipment is subjected to a motion generated b summing a group of decaying sinusoids (see 5.3.1.3 where the frequencies of the component signals shoul be spaced at 1/3 octave or narrower frequency interval to cover the range required by the SRS. The decay rat and amplitude should be varied at each frequency t optimize the spectral fit of the TRS to the SRS.

5.3.3 Verification testing

Verification testing is used to determine or confirm on or more of the following: natural frequencies, dampin dynamic response, or stiffness of the system or component. Some of the commonly used test methods used in verification testing are shown in Figure 5.1 as 'Other test methods'. The data obtained from these tests can be used with a suitable method of analysis as per Section 4 to achieve seismic qualification of the equipment.

5.4 Seismic qualification testing documentation

For seismic qualification by testing, the test report shall include the following:

- Name and address of test facility.
- Statement of test objective.
- Equipment specifications and pertinent drawings.
- Qualification requirements and specified response spectrum.
- Description of test method and reasons for choice.
- Description fo test equipment, test mounting, calibration etc..
- Test data.
- Results and conclusions.
- Other pertinent information, e.g. method of mounting used in testing, selection of damping, derivation of test input waveform etc..
- Approving signature and date.

If proof of performance is obtained by extrapolation from a similar previously-qualified item, this must be well justified. A qualification report would comprise presentation of a test report of the original equipment with justification of extrapolation, supplemented by additional test and/or analytical data if relevant.

TABLE 5.1 FACTORS TO ACCOUNT FOR MULTI-FREQUENCY AND MULTI-DIRECTIONAL EFFECTS

Nature of dynamic testing	Factor
Bi-directional Multi-frequency	1.0
Uni-directional Multi-frequency	1.4
Bi-directional Single frequency	1.3
Uni-directional Single frequency	1.5

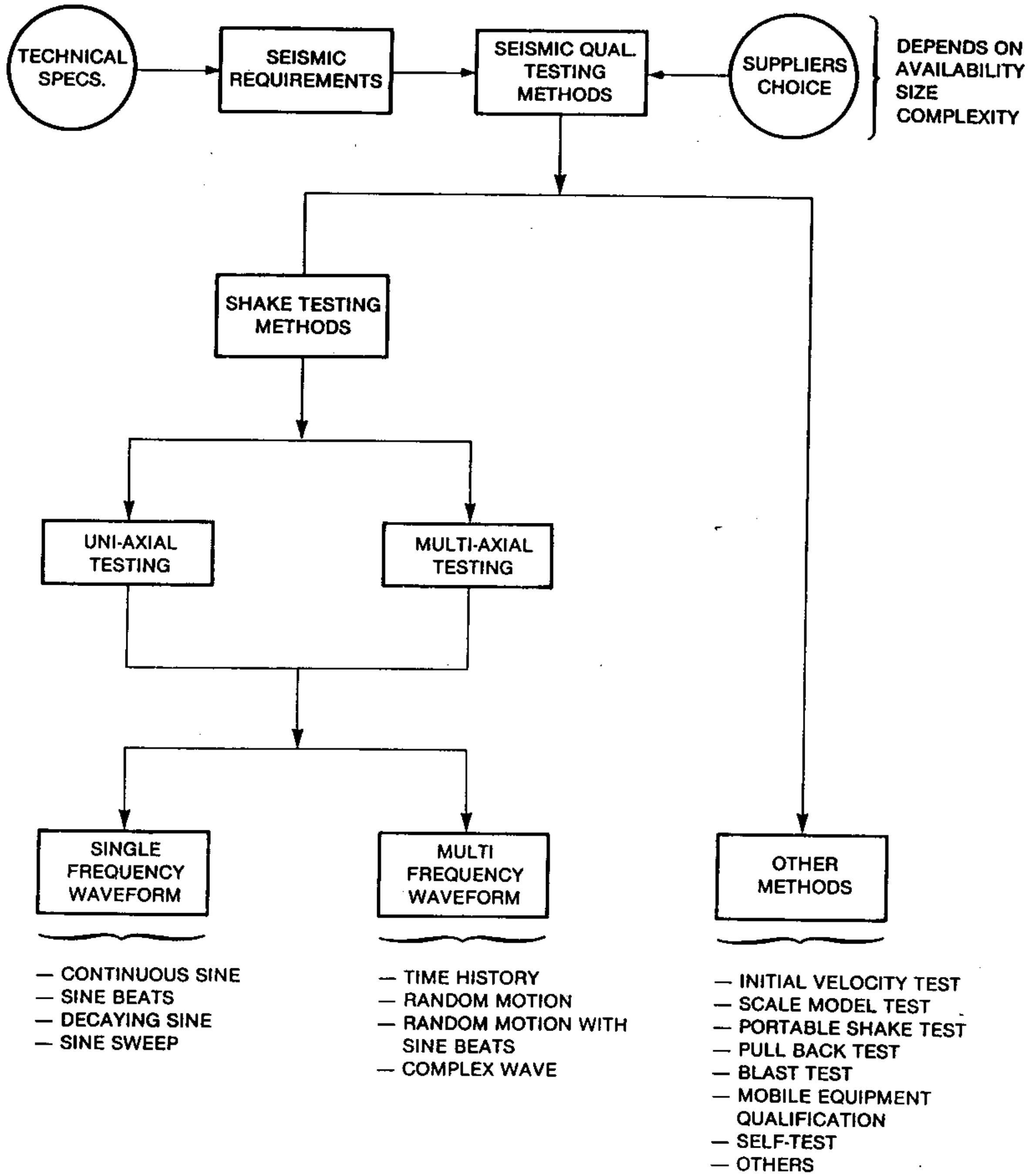


FIGURE 5.1 FLOW CHART OF SEISMIC QUALIFICATION BY TESTING

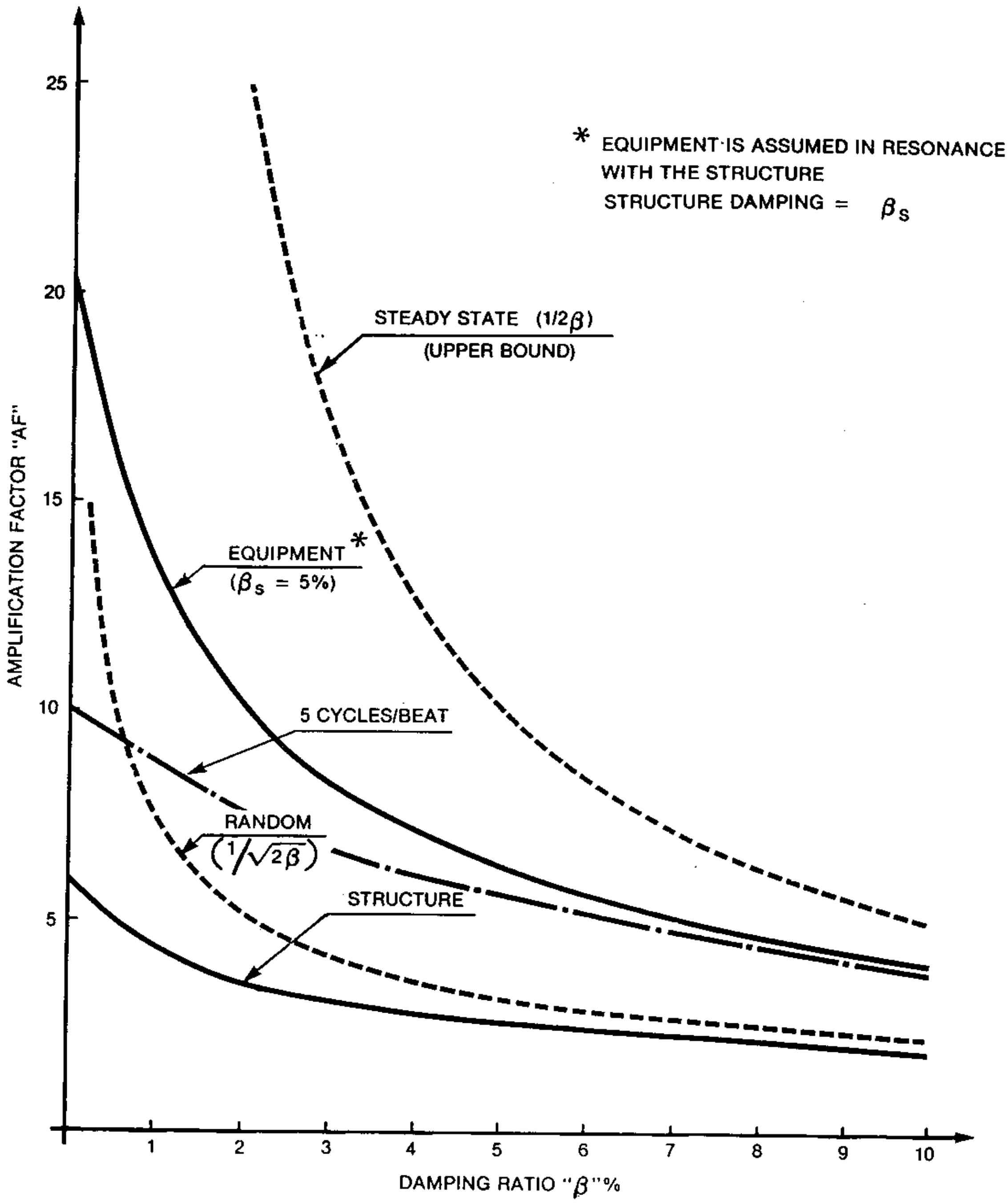


FIGURE 5.2 EFFECT OF DAMPING ON STRUCTURE AND EQUIPMENT RESPONSE

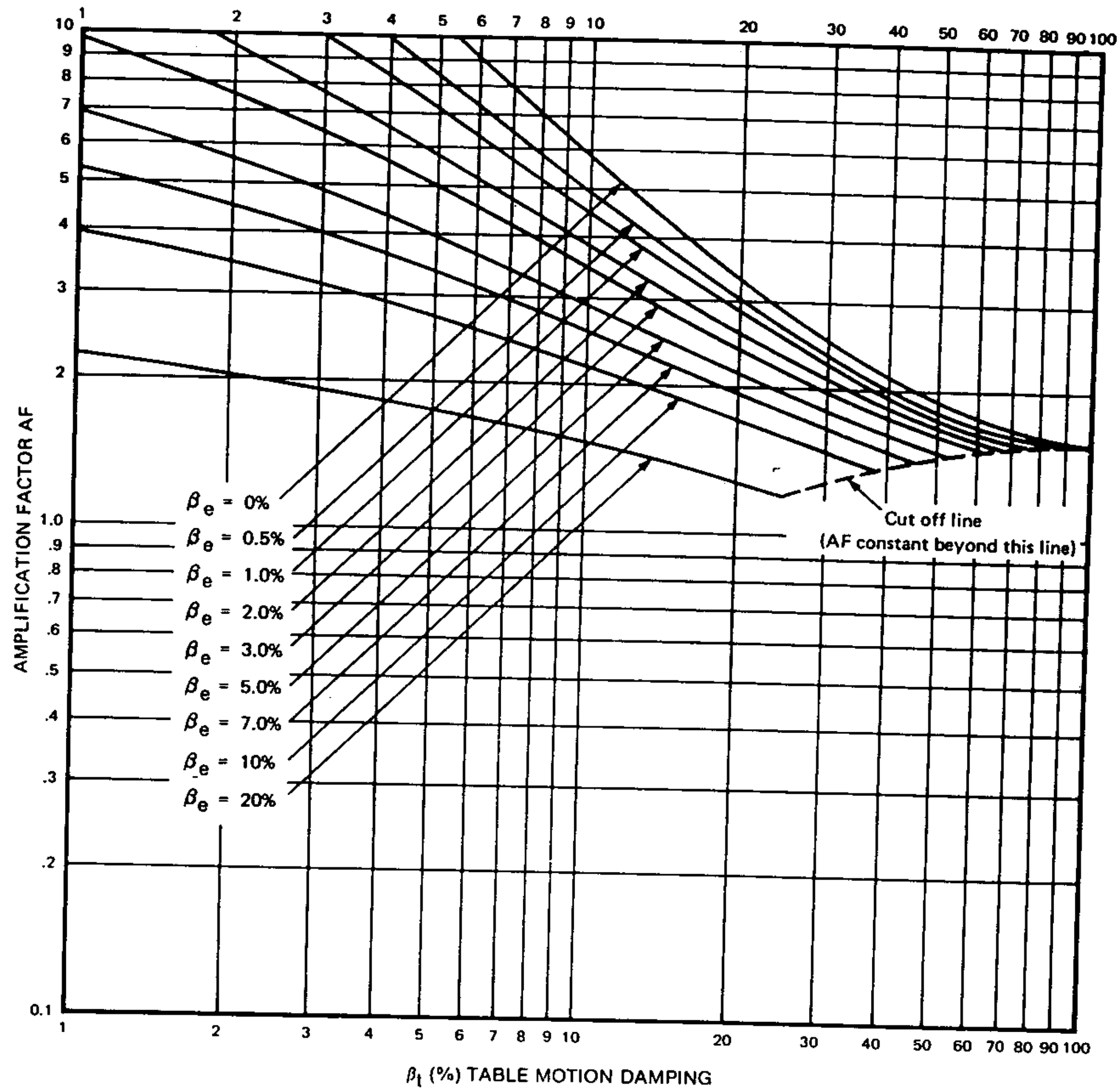


FIGURE 5.3 AMPLIFICATION FACTOR: EQUIPMENT-TO-TABLE

6. SEISMIC DESIGN CRITERIA

6.1 General

This section defines either directly or by reference to appropriate codes and standards, the design criteria, load combinations and allowable stresses governing the seismic design of structures and components in CANDU nuclear power plants.

6.2 Structures

6.2.1 Containment structures

The design criteria, allowable stresses and load combinations for the seismic design of concrete containment structures shall comply with the requirements of CSA Standard N287.3 (Design Requirements for Concrete Containment Structures for CANDU Nuclear Power Plants, Reference 12). See Note in Table 6.1.

6.2.2 Other structures

1) For seismic design of structures other than containment structures, e.g., reactor building and vacuum building internal structures, service building, secondary control area, fuel and waste management building, auxiliary buildings, etc., load combinations and allowable stresses shall be as given in accordance with the National Building Code of Canada (Reference 1) except as stated in Table 6.1.

2) Structures, parts of structures, and support structures which do not come under the above shall be designed to the requirements of sub-section 4.1.9 of the National Building Code of Canada or by the applicable building code, as a minimum, except that the seismic load shall be obtained from 4.2.4.

6.3 Components

6.3.1 General

Seismic load combinations for components shall be determined by the seismic classification of the component as determined by safety or economic considerations.

Load combinations for seismic design of components shall comprise the appropriate earthquake loading (DBE or SDE) combined together with non self-limiting loads leading to primary stresses, together with fatigue analysis per 4.15. The load combinations and allowable stresses shall be as given in this section.

For seismic analysis, transient loads of sufficiently long duration or high frequency as defined in 3.4 shall be considered as normal or upset loads, as applicable.

6.3.2 Components requiring seismic qualification

The following discusses the load combinations and allowable stresses* for components to be seismically qualified:

1) Components, component supports and parts of components of a structural nature which can be considered to be part of the building structure shall be designed as per 6.2.2.

* In some cases, deformation of the component may govern instead of stress, e.g., where only a limited movement is acceptable because of clearance, functional or other reasons connected with safe, reliable service.

TABLE 6.1 FACTORED RESISTANCE LOAD COMBINATION TABLE

	Factored resistance	
Load combination	**Structural steel**	**Concrete**
1) Normal + SDE	In accordance with NBCC 1977, except that the load factor (α) shall be in accordance with CSA-S16.1 (1974), and the importance factor (γ) and load combination factor (ψ) shall each = 1	In accordance with NBCC 1977, except that the load factor (α) shall be in accordance with CAN-[redacted] M77; the importance factor (γ) and the load combination factor (ψ) shall each = 1 A23.3
2) Abnormal/Environmental* + DBE (see note)	In accordance with CSA-S16.1 (1974) except that the load factor (α), importance factor (γ) and load combination factor (ψ) shall each = 1.	In accordance with NBCC 1977, except that the load factor (α), importance factor (γ) and the load combination factor (ψ) shall each = 1.

Note: For dynamic analysis purposes, live loads shall be determined on the basis of the combined mass of rigidly-mounted equipment at each level or node.

* For Abnormal/Environmental Load Combination refer to CSA Standard N287.3 (Reference 12).

TABLE 6.2 STRESS LIMITS FOR SEISMIC DESIGN OF CLASS 1* AND CLASS MC* COMPONENTS AND PLAT AND-SHELL TYPE COMPONENT SUPPORTS DESIGNED TO SUB-SECTION NF*

Service limits	Earthquake loading	Seismic fatigue analysis	Stress type	Stress limit	Remarks
Level A	No	No	P_m $P_m + P_b$	S_m $1.5\ S_m$	Design condition limits*
Level B	No	No	P_m $P_m + P_b$	$1.1\ S_m$ $1.65\ S_m$	Only for pressure exceeding design pressure
Level C	Yes Yes	Fatigue analysis per section 4.15 (See Note 2)	P_m $P_m + P_b$	$1.2\ S_m$ or S_y $1.8\ S_m$ or $1.5\ S_y$ or $0.8\ C_L$	the greater value applies to components. The lesser value applies to plate-and-shell type component supports (see Note 1).

S_m = Design stress intensity

S_y = Minimum yield strength at design temperature

P_m = Primary membrane stress

P_b = Primary bending stress

1) A maximum of $0.8\ S_y$ or $1.2\ S_y$ respectively, recommended where distortion controls design.

2) For seismic fatigue analysis, peak stresses shall be derived from the combined effects of inertial and anchor-point displacement responses.
The total fatigue usage factor shall also include all other usage factors due to specified normal and abnormal plant operating conditions, as called for in the appropriate sub-section of the ASME Code*. The combined fatigue usage factor may be greater than 1 (See Reference 11).

* ASME Boiler and Pressure Vessel Code, Section III, Division I (Reference 13).

2) Pressurized components, and parts or supports of such components, designed to the applicable sub-sections of Section III of the ASME Boiler and Pressure Vessel Code, shall be designed to Level 'C' (Emergency Condition, Reference 13) stress limits, as defined in Tables 6.2, 6.3 and 6.4, as applicable.

3) The load combinations, allowable stress limits and fatigue analysis requirements for piping designed to Section III of the ASME Code shall be in accordance with Table 6.5 (Class 1) and Table 6.6 (Class 2, Class 3, and ANSI B31.1, References 13 and 14), respectively.

4) The design criteria for components fabricated from structural steel and not designed to Section III of the ASME Boiler and Pressure Vessel Code shall be selected to comply with the requirements of Table 6.1.

5) Refer to 6.4 for seismic design criteria for the design of anchors, supports, restraints, snubbers etc., for components requiring seismic qualification.

6.3.3 Other components

1) Components which are not specifically required t be seismically qualified, but whose failure, deforma tion of dislocation during an earthquake could impai the performance of nearby safety-related compo nents shall be designed by means of (i) separation, (i protective barriers or (iii) supports, anchors restraints, bracing, hangers, etc., for these com ponents, which are capable of resisting the SDE o DBE, as applicable. Load combinations an allowable stresses for such supports, anchors restraints, bracing, hangers, etc., and in the attach ment points of such equipment, shall be as give under 6.3.2.

2) The supports, restraints, anchors, hangers, etc., fo all other components which do not fall under th above,shall be designed to comply with sub-sectio 4.1.9 of the National Building Code of Canad (Reference 1) or the relevant local building code, a minimum, except that the seismic load shall be deri ed from 4.2.4.

6.4 Supports, restraints, bracing, anchors, snubbers and dampers

6.4.1 Component supports

1) Unless otherwise permitted in the design specification, components shall be anchored to their structural supports. If components must be suspended, lateral bracing shall be designed and installed to prevent uncontrolled displacements or instability. Where such a component must be allowed to move (e.g. thermal expansion) its supports shall contain elements for damping or restricting the magnitude of dynamic movement within bounds.

2) Where vibration isolation of components is necessary, suitable constraints shall be added to restrict movement within design limits. Where com-

TABLE 6.3 STRESS LIMITS FOR SEISMIC DESIGN OF CLASS 2* AND CLASS 3* COMPONENTS

Service limits	Earthquake loading	Seismic fatigue analysis	Stress type	Stress limit	Remarks
Level A	No	No	P_m $P_m + P_b$	S 1.5 S	
Level B	No	No	P_m $P_m + P_b$	1.1 S 1.65 S	
Level C	Yes	No seismic fatigue analysis required for Class 3 components. For Class 2 components refer to 4.15	P_m $P_m + P_b$	1.5 S 1.8 S	See Table 6.2 Note 2 Class 2 components

S = Allowable stress
P_m = Primary membrane stress
P_b = Primary bending stress

* Sub-section NC (Class 2) and sub-section ND (Class 3) of the ASME Boiler and Pressure Vessel Code, Section III, Division I (Reference 13).

TABLE 6.4 STRESS LIMITS FOR SEISMIC DESIGN OF LINEAR COMPONENT SUPPORTS* (INCLUDING SUB-SECTION NF), RESTRAINTS AND BRACING**

Service limits	Earthquake loading	Seismic fatigue analysis	Stress type	Stress limit	Remarks
Level A & B**	No	No	F_t F_v F_b	0.6 S_Y 0.4 S_Y 0.60 S_Y (min)	0.60 S_Y for high-strength bolts 0.25 S_Y for high-strength bolts 0.75 S_Y for solid sections 0.66 S_Y for flanges of compact sections (See Note 1 re combinations)
Level C**	Yes	No	F_t F_v F_b	0.80 S_Y 0.53 S_Y 0.80 S_Y (min)	0.60 S_Y for high-strength bolts 0.25 S_Y for high-strength bolts 1.0 S_Y for solid sections 0.88 S_Y for flanges of compact sections (See Note 1 recombinations)

S_Y = Minimum yield strength at design temperature
F_t = Tensile stress averaged over full cross-sectional area of member
F_v = Shear stress averaged over full cross-sectional area of member
F_b = Maximum bending stress at extreme fibre of member cross-section

* See Table 6.2 for plate-and-shell type component supports designed to Sub-section NF
** ASME Boiler and Pressure Vessel Code, Section III, Division I (Reference 13)

Notes: 1) For tension plus bending, apply linear interaction formula, using individual stress components and their respective limits.

For tension plus shear, apply elliptical (square-law) interaction formula, using individual stress components and their respective limits.

ponents are allowed to sway, connections require special design considerations which shall be incorporated into the mathematical model.

3) The different damping properties and amplification factors shall be included in the analyses.

6.4.2 Piping supports

Piping attachments to the supporting system shall be designed to accomodate seismic loads. Piping components shall be supported from a single structural unit where possible. In cases where pipe supports are attached to more than one structural unit, the relative deflections of these attachment points shall be included in the design analysis. Similarily, the combined effect of the dynamic movement of the supports on the inertial response of the piping system shall be taken into account.

Piping components required to operate at higher temperatures are of special concern because the flexibility requirements for thermal expansion may be incompatible with the stiffness required to accomodate seismic loadings. Some components may require the use of damping devices, which permit the required slow thermal movement but resist the rapid movement resulting from seismic and other dynamic loadings (see 6.4.4). Where such displacement-limiting and damping devices are used, they shall be represented in the seismic analyses, and the restraint forces imposed on the system by these devices shall be included in the thermal expansion analyses.

6.4.3 Supports, bracing, hangers, restraints and anchors

a) Redundancy shall be used in the design of component supports, bracing, seismic restraints and anchors. At least two anchors shall be used per locations, each capable of carrying the full design load. Cast-in anchors shall be used wherever possible.

b) Expansion anchors are to be avoided if possible. Where unavoidable, expansion anchors shall be of a type proven to be resistant to slippage or loosening under severe vibration or impact loading.

c) Embedded anchors shall be used with a minimum factor of safety of 4 against pull out and other possible modes of failure. Anchor bolts should be prestressed to loads equalling or exceeding their maximum operating load, including seismic loads.

d) Supports, bracing and restraints shall be checked for stability against buckling or collapse under seismic loading, when combined with all other applicable loads.
Sub-section NF (Component Supports) of the ASME Boiler and Pressure Vessel Code, Section III (Reference 13) shall be used for designing such supports; with reference to Appendix XVII of the same code for analyzing linear-type supports. When seismic conditions apply, the total allowable loading stress for such linear-type supports may be increased by 33% (Level 'C' Service).
The minimum factors of safety against buckling collapse of linear-type supports under seismic p[...] other applicable loads shall be as follows:

For direct axial compressive stress (where allowable stress is based on yield strength)	1.
For combined axial compression and bending moment (based on Euler load, as defined in Paragraph 4221 of Appendix XVII)	1.

In the case of axial compressive loads combin[...] with bending moments, appropriate beam-colum[...] type formulae are recommended for determinin[...] combined stresses; deflections and critical bucklin[...] loads. Combined stresses shall also be checked u[...]ing the appropriate stress-interaction formula give[...] in Paragraph 2215 of Appendix XVII (Reference 13[...] The higher stresses computed by the two method[...] shall be used for design.
The maximum 'effective slenderness ratios', K ℓ/[...] as defined in Appendix XVII (Reference 13) f[...] various structural members, shall be as follows:

For main **compression** members or columns	12
For bracing, restraints; secondary **compression** members	2
For main **tension** members	24
For bracing, restraints; secondary **tension** members	30

For static stability analysis during an earthquak[...] see 4.7.

e) For equipment on sliding supports or where motio[...] limiting stops are provided with a clearance, a[...] analysis completely neglecting the effect of th[...] restraints may be considered to be conservative.

6.4.4 Dampers and snubbers

a) Hydraulic type dampers or snubbers containing flu[...] and requiring dynamic seals shall be avoid[...] wherever possible.

b) Inertia-friction devices, not requiring regul[...] maintenance, and capable of operating indefinite[...] in the heat and radiation environment surroundi[...] the pipes or other components to which the devic[...] are attached, may be employed, provided they a[...] thoroughly tested and proven before use, and can [...] removed for periodic in-service inspection as r[...]quired by CSA Standard N285.4 'Periodic Inspect[...] of CANDU Nuclear Power Plant Componen[...] (Reference 15).

c) Passive devices such as motion-limiting stops are preferred wherever possible. Impact loads shall be taken into account in the design of such devices and their anchors. Non-linear dynamic analyses, using time-history method, shall be employed where high impact forces are likely to be experienced during the design earthquake and where such non-linear effects can significantly alter the dynamic behaviour of the vibrating system or component. Otherwise, a linear dynamic analysis may be undertaken, provided that suitable adjustments are made for the expected spring properties and coefficients of restitution of the stops (this will usually require an iterative or bounded approach, where the most unfavourable values are used for design purposes).

TABLE 6.5 STRESS LIMITS FOR SEISMIC DESIGN OF CLASS 1* PIPING

Loading	Equation ASME*	Earthquake loading	Stress limits	Remarks
Sustained**	9	NO	$1.50S_m$	
Expansion	10	No	$3.0S_m$	Limits mechanical and thermal expansion stresses per NB-3653.1
Sustained** + Occasional	9	Yes	$2.25S_m$	
Fatigue	11 14	Yes Yes		See section 4.15 Use equation 14 only if equation 10 is not satisfied
Alternative analysis				
Elastic-plastic analysis	12	No	$3.0S_m$	Alternative analysis method, to be used only if equation 10 is not satisfied.
Discontinuity analysis	13	Yes	$3.0S_m$	See note below † re equation 13.

* Reference NBN-3650 of ASME Boiler and Pressure Vessel Code Section III, Division 1, (Reference 13).

** Sustained loads refers to non self-limiting loads, e.g. weight, pressure, mechanical loads, etc..

† Equation 13 conservatively checks for ratchetting due to primary bending moments. If equation 13 cannot be met, a more rigorous bending-ratchetting analysis may be performed.

TABLE 6.6 STRESS LIMITS FOR SEISMIC DESIGN OF PIPING (CLASS 2*, CLASS 3*, AND ANSI B31.1**)

No.	Loading NC-3650	Equation numbers ASME ND-3650	ASME B31.1	ANSI loading	Earthquake limits	Stress	Remarks
1	Sustained	8	8	11	No	S_h	
2	Sustained + Occasional	9	9	12	Yes	$1.2S_h$ (ANSI B31.1) $1.8S_h$ Class 2 Class 3	
3	Expansion	10	10	13	No	S_A	If equation 10 (eq. 13 in B31.1) is not satisfied, check equation 11 (eq. 14 in B31.1).
4	Sustained + Expansion	11	11	14	Yes	$(S_h + S_A)$	Seismic anchor movements shall be considered in equations 10 and 11 (equations 13 & 14 - B31.1), if they are excluded from equation 9 (eq. 12 - B31.1)

S_h = Basic material allowable stress at max. temperature

S_A = Allowable stress range for expansion stresses

* NC-3650 (Class 2), ND-3650 (Class 3) of ASME Boiler and Pressure Vessel Code, Section III, Division 1 (Reference 13)

** American National Standard Code for Power Piping, ANSI B31.1 (Reference 14).

REFERENCES

(1) National Building Code of Canada, NRCC No. 13982.

(2) *Seismic Qualification of CANDU Nuclear Power Plants,* Canadian Standards Association Standard N289 (in preparation)

(3) **Stoykovich, M.,** *Methods of Determining Floor Response Spectra,* Symposium on Structural Design of Nuclear Power Plant Facilities, ed., J.I. Abrams and J.D. Stevenson, of Pittsburg, December 1972.

(4) **Duff, C.G.,** *Earthquake Response Spectra for Nuclear Power Plants* using Graphical Methods, CSNI specialist meeting on anti-seismic design of nuclear power plant installations, Paris (France), December 1975.

(5) **Aziz, T.S. and Biswas, J.K.,** *Spectrum-Compatible Time-Histories for Seismic Design of Nuclear Power Plants,* Proceedings of Third Canadian Conference on Earthquake Engineering - Vol. 1, Montreal, June 1979.

(6) **Aziz, T.S.,** *Decoupling Criteria for Seismic Analysis of Nuclear Power Plant Systems,* Paper no. 78-PVP-27, ASME/CSME Pressure Vessel and Piping Conference, Montreal, Canada, June 25-30, 1978.

(7) *Nuclear Reactors and Earthquakes,* U.S. Atomic Energy Commission, Division of Reactor Development, report TID-7024, Washington D.C., August 1963.

(8) **Housner, G.W.,** *Dynamic Pressures on Accele- ted Fluid Containers,* Bull. Seismological Soci- of Am. 47(1), Jan. 1957.

(9) American Society of Mechanical Engine Boiler and Pressure Vessel Code — Code Ca Nuclear Components, 1977 Edition.

(10) Criteria of the American Society of Mechanic Engineers Boiler and Pressure Vessel Code Design by Analysis in Sections III and VIII (Div. Third Edition, Draft 9/1/77.

(11) **Duff C.G. and Heidebrecht A.C.** *Earthqua Fatigue Effects on CANDU Nuclear Power Pla Equipment,* presented at the Third Canadian Co ference on Earthquake Engineering, Montre Canada, June 3-5, 1979.

(12) *Design Requirements for Concrete Containme Structure for CANDU Nuclear Power Plan* Canadian Standards Association standa N287.3.

(13) American Society of Mechanical Enginee Boiler and Pressure Vessel Code Section III, Di sion 1, Nuclear components.

(14) American National Standard Code for Power ing, ANSI B31.1

(15) Periodic inspection of CANDU nuclear pov plant components, Canadian Standards Assoc tion standard N285.4.

APPENDIX

MULTIPLE-SUPPORT EXCITATION

1. INERTIAL EFFECT (n lumped masses)

Figure A1.1(a) shows a simply-supported, lumped-mass system represented by lumped masses M_1, M_2, M_3, ..., M_i, ..., M_n. A and B are the supports receiving different seismic excitations.

For any node M_i, the modal accelerations due to motions at A and B (receiving different seismic excitations) given by $(\ddot{Y}_{in})_A$ and $(\ddot{Y}_{in})_B$, respectively, are as follows:

$$(\ddot{Y}_{in})_A = (S_n)_A(\Gamma_n)_A\,\phi_{in}$$

$$(\ddot{Y}_{in})_B = (S_n)_B(\Gamma_n)_B\,\phi_{in}$$

$$\text{where } (\Gamma_n)_A = \frac{\sum M_i\,(\eta_i)_A\,\phi_{in}}{\sum M_i\,(\phi_{in})^2}$$

$$(\Gamma_n)_B = \frac{\sum M_i\,(\eta_i)_B\,\phi_{in}}{\sum M_i\,(\phi_{in})^2}$$

ϕ = shape factor
i = number of mass or mode point
n = number of mode
A = subscript referring to end A or response due to motion at end A only
B = subscript referring to end B or motion therefrom
η = influence coefficient
Γ_n = participation factor of mode n
S = spectral acceleration
$\ddot{Y}_{in}$ = modal acceleration of mass M_i in mode n

a) Motions at A and B are out-of-phase:
The modal acceleration at M_i is given by:

$$\ddot{Y}_{in} = \sqrt{(\ddot{Y}_{in})_A^2 + (\ddot{Y}_{in})_B^2}$$

b) Motions at A and B are in-phase:

$$\ddot{Y}_{in} = |\ddot{Y}_{in}|_A + |\ddot{Y}_{in}|_B$$

1.1 Inertial effect (One lumped mass)

If the mass of the system is represented by a lumped mass M_o at the centre C (Fig. A1.1(b)), and $\ddot{Y}_A$ and $\ddot{Y}_B$ are the seismic excitations at A and B, respectively, the net acceleration of the mass M_o at C is given by:

a) $\ddot{Y}_A$ and $\ddot{Y}_B$ are in-phase:

$$\ddot{Y}_{net} = \frac{|\ddot{Y}_A| + |\ddot{Y}_B|}{2}, \text{ if } \ddot{Y}_A \text{ and } \ddot{Y}_B \text{ are in-phase.}$$

$$= \ddot{Y}, \text{ if } \ddot{Y}_A = \ddot{Y}_B = \ddot{Y}$$

b) $\ddot{X}_A$ and $\ddot{X}_B$ are out-of-phase:

$$\ddot{Y}_{net} = \sqrt{\left(\frac{\ddot{Y}_A}{2}\right)^2 + \left(\frac{\ddot{Y}_B}{2}\right)^2}$$

$$= \frac{1}{\sqrt{2}}\ddot{Y}, \text{ if } \ddot{Y}_A = \ddot{Y}_B = \ddot{Y}$$

1.2 Anchor point movements

The maximum movements (Y_{net}) of a component due to anchor point movements Y_A and Y_B at ends A and B, respectively, are given by:

a) Y_A and Y_B are randomly phased:

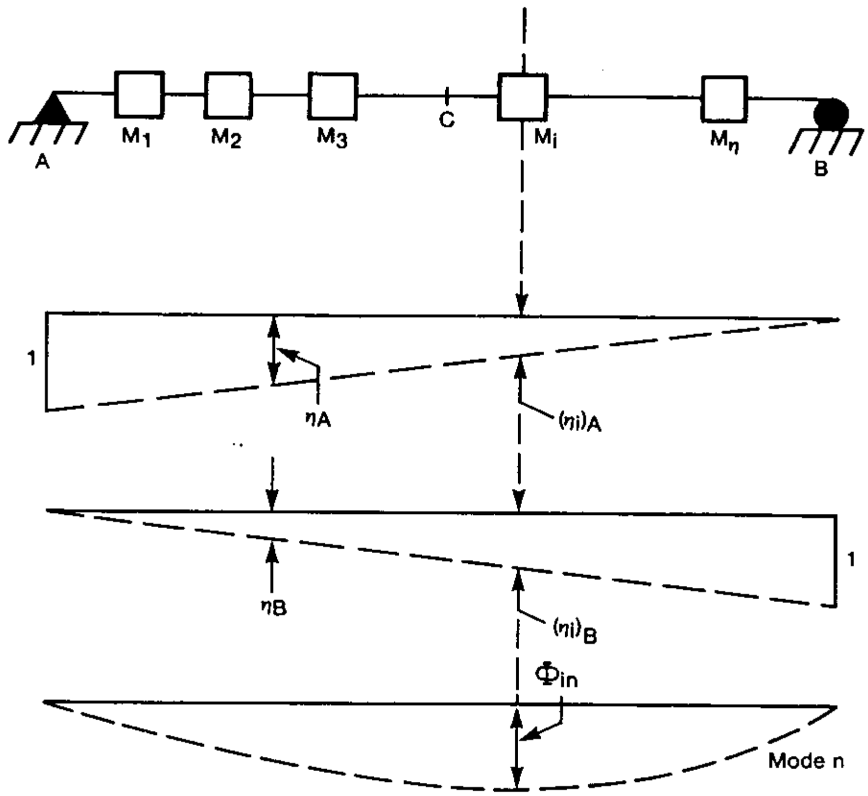
$$Y_{net} = \sqrt{Y_A^2 + Y_B^2} = \sqrt{2}Y, \text{ if } Y_A = Y_B = Y$$

if the ends are connected to points having different motions, e.g., if connected to two floors or to two different seismic inputs.

b) Y_A and Y_B are 180° out-of-phase, then the combined movement Y_{net} is given by:

$$Y_{net} = |Y_A| + |Y_B|$$

$$= 2Y, \text{ if } Y_A = Y_B = Y$$



η_A AND η_B ACT AS INFLUENCE COEFFICIENTS FOR UNIT MOTION AT A AND B, RESPECTIVELY

FIGURE A1.1(a)

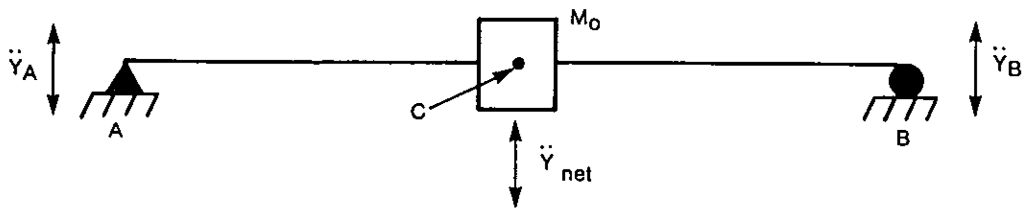


FIGURE A1.1(b)

FIGURE A1 COMBINATION OF RESPONSES DUE TO MULTIPLE-SUPPORT EXCITATION (INERTIAL EFFECT)

(a) GENERAL LUMPED MASS SYSTEM

(b) LUMPED MASS CONCENTRATED AT CENTRE OF ELEMENT