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SEISMIC DESIGN FEATURES OF THE ACR™ NUCLEAR POWER PLANT

Medhat Elgohary, Ayman Saudy and Tarek Aziz

Atomic Energy of Canada Limited
Sheridan Park Research Community
Mississauga, Ontario, Canada

ABSTRACT

Through their worldwide operating records, CANDU™ Nuclear Power Plants (NPPs) have repeatedly demonstrated safe, reliable and competitive performance. Currently, there are fourteen CANDU 6 single unit reactors operating or under construction worldwide. Atomic Energy of Canada Limited's (AECL) Advanced CANDU Reactor - the ACR™ - is the genesis of a new generation of technologically advanced reactors founded on the CANDU reactor concept. The ACR is the next step in the evolution of the CANDU product line. The ACR products (ACR-700 and ACR-1000) are based on CANDU 6 (700 MWe class) and CANDU 9 (900 MWe class) reactors, therefore continuing AECL's successful approach of offering CANDU plants that appeal to a broad segment of the power generation market. The ACR products are based on the proven CANDU technology and incorporate advanced design technologies.

The ACR NPP seismic design complies with Canadian standards that were specifically developed for nuclear seismic design and also with relevant International Atomic Energy Agency (IAEA) Safety Design Standards and Guides. However, since the ACR is also being offered to several markets with many potential sites and different regulatory environments, there is a need to develop a comprehensive approach for the seismic design input parameters. These input parameters are used in the design of the standard ACR product that is suitable for many sites while also maintaining its economic competitiveness. For this purpose, the ACR standard plant is conservatively qualified for a Design Basis Earthquake (DBE) with a peak horizontal ground acceleration of 0.3g for a wide range of soil/rock foundation conditions and Ground Response Spectra (GRS). These input parameters also address some of the current technical issues such as high frequency content and near field effects.

In this paper, the ACR seismic design philosophy and seismic design approach for meeting the safety design requirements are reviewed. Also the seismic design features including the design soil/rock foundation profiles and input GRS that are used in the seismic design and qualification of the ACR are presented. It is concluded that the selected seismic design input parameters for the ACR plant meet current international technical and regulatory requirements.

Key Words: AECL, CANDU, ACR, seismic, safety, design, earthquake, IAEA, foundations, advanced, model, structure.

1. INTRODUCTION

AECL's Advanced CANDU Reactor is the genesis of a new generation of technologically advanced reactors founded on the CANDU reactor concept. The ACR is the next step in the evolution of the CANDU product line. The ACR products (ACR-700 and ACR-1000) are based on CANDU 6 (700 MWe class) and CANDU 9 (900 MWe class) reactors, continuing AECL's successful approach of offering reactors that appeal to a broad segment of the power generation market. The ACR products are based on the proven CANDU technology and incorporate advanced design features. Figure 1 shows the layout of the major buildings of the two-unit ACR NPP.

CANDU NPP structures, systems and components are designed to sustain the effects of earthquakes expected at the NPP site. The seismic design of the standard ACR NPP complies with Canadian standards that were specifically developed for nuclear seismic design and also with relevant IAEA Safety Design Standards and Guides. However, since the ACR is also being offered to several markets with many potential sites and different regulatory environments, there is a need to develop a comprehensive approach for the seismic design input parameters. These input parameters are used in the design of a standard ACR product that is suitable for many sites while also maintaining its economic competitiveness. These input parameters also cater for some of the current technical issues such as high frequency content and near field effects.

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In this paper, the ACR seismic design philosophy and seismic design approach for meeting the safety design requirements are reviewed. Also, the seismic design input parameters; including the design soil/rock foundation profiles and input GRS, as well as the plant seismic design features are presented.

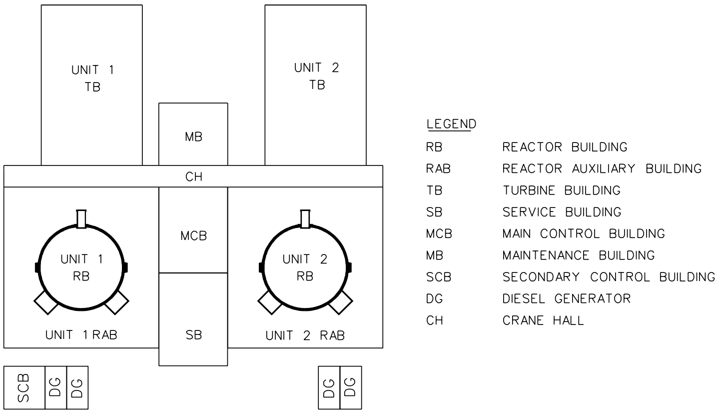


Figure 1: ACR Plant Layout

2. SEISMIC DESIGN PHILOSOPHY

2.1 General

CANDU NPPs are designed to satisfy the requirements of the Canadian Standards Association's nuclear seismic design series N289, References 1 to 5. This series of standards, which describes the technical requirements, criteria, procedures and methods for seismic qualification of CANDU NPPs, is similar to other international standards and complies with the IAEA seismic safety guides.

2.2 Seismic Levels

a) Safety-related Structures, Systems and Components

Structures, systems and components having safety-related functions are designed to withstand more severe but less probable earthquakes. Namely, two earthquake levels are developed per Reference 3, termed the DBE and the Site Design Earthquake (SDE). These levels of design earthquakes are defined below:

1) The Design Basis Earthquake (DBE)

The Design Basis Earthquake (sometimes referred to as the "Safe Shutdown Earthquake") also designated as "SL-2" in the IAEA Guide 50-SG-S1, Reference 6. The DBE means an engineering representation of the potentially severe effects of earthquakes, applicable to the site, that have sufficiently low probability of being exceeded during the lifetime of the plant

2) Site Design Earthquake (SDE)

For certain conditions, including some event combinations, post-accident inspection, national licensing requirements and economic considerations, a second level earthquake, known as the Site Design Earthquake, is considered in the design. The SDE is an intermediate level earthquake, similar to "SL-1" of Reference 6. This earthquake level corresponds to a less severe but more likely earthquake load condition with different safety implications from the DBE.

The SDE means an engineering representation of the effects at the site of a set of possible earthquakes with an occurrence rate, based on historical records, not greater than 0.01 per year.

b) Non-safety related Structures, Systems and Components

Non-safety related structures, systems and components are designed to an earthquake similar to what is adopted for normal industrial plants and public buildings. For the ACR plant, this earthquake level is called the Generic Design Earthquake (GDE) and is used as a minimum level for designing all structures and equipment in the ACR plant.

2.3 Seismic Categories

Two categories, “A” and “B”, are defined to identify the extent to which components must remain operational during and/or after an earthquake.

a) Category “A” Components

Those which must retain their pressure boundary integrity, structural integrity or passive function (i.e., components which do not have an active mechanical function but may have electrical or load bearing function) during and/or following an earthquake.

b) Category “B” Components

Those which must retain their pressure boundary integrity and in addition must remain operable during and/or following an earthquake. This category also includes components that are not part of the pressure boundary, but must operate during and/or following an earthquake.

2.4 Objectives

The safety objective of the seismic design for the plant is to have sufficient capability to perform the following essential safety functions:

a) shut the reactor down and maintain it in the shutdown state,

b) cool the fuel in the reactor and in the fuel handling system to the extent that releases outside containment remain within the dose limits for the event,

c) maintain the containment boundary and any necessary associated systems,

d) maintain sufficient qualified instrumentation for the operator to control and monitor the plant from a seismically qualified area, and

e) maintain the integrity of structures and systems outside containment such as the spent fuel bay, which could cause radioactivity releases beyond allowable accident release limits.

2.5 Safety Functions

The systems and equipment that must be qualified to perform the safety functions, to maintain the release of radioactivity within the regulatory dose limits, are discussed below. Appendix A shows schematically the seismic qualification levels for the ACR plant major systems.

a) The ability to shutdown the reactor shutdown:

- The two independent shutdown systems (Shutdown Systems 1 and 2) are qualified to shut the reactor down automatically, and to be manually actuated from a seismically qualified area.

b) The ability to remove decay heat:

- The Heat Transport System (HTS) pressure boundary, including the fuel, fuel channels, feeders, headers, pumps, pressurizer, steam generators, and connected subsystems and supporting structures are seismically qualified to the DBE level. This ensures that a loss of coolant accident does not occur as a result of the earthquake.
- The Moderator System and Calandria Shield Tank are qualified to DBE to support the HTS safety functions
- If the normal non-DBE qualified feedwater system fails, the reserve water system is a qualified source of feedwater, with an inventory suitable until the initiation of the Long Term Cooling (LTC) System.
- The main steam piping up to the Main Steam Safety Valves (MSSV) and Main Steam Isolation Valves (MSIV) are qualified to ensure that the residual and decay heat can be discharged to the atmosphere. The pipe anchors, downstream of the MSIV, are designed to withstand the loading imposed by any failed steam lines.
- The LTC system is seismically qualified to provide cooling in the long term for a Loss of Cooling Accident (LOCA) and to remove decay heat indefinitely in the long term with the HTS pressure boundary intact, and is supplied with seismically qualified electrical power and service water.
- The Emergency Coolant Injection (ECI) system is seismically qualified to cater for pre-existing small leaks and any shrinkage created through the depressurization of the HTS.
- Cooling water to seismically qualified components, including the LTC heat exchangers, is supplied by seismically qualified service water systems i.e. Raw Service Water and Recirculating Cooling Water systems (RSW/RCW).

c) The ability to maintain a barrier to limit the release of radioactive material:

- To contain radioactive releases, the plant design provides a succession of seismically qualified barriers, namely, the fuel sheath, the HTS boundary, the containment envelope, the fuelling machine and the spent fuel transfer system.
- The containment envelope is qualified to ensure that the dose limits for an earthquake postulated initiating event are satisfied.
- The containment system, including containment isolation and hydrogen control, are seismically qualified.
- Suitable pressure and temperature conditions shall be maintained within the reactor building to ensure the integrity of the containment boundary, and operation of seismically qualified systems.
- Structures or components outside the containment envelope, whose failure could result in the dose limits being exceeded, are also seismically qualified. This includes the equipment in the spent fuel storage bay.
- The containment structure is qualified to withstand the loads due to a DBE, combined with the internal pressure existing after a LOCA, and a "reduced accident pressure", due to the failure of piping or components that are not qualified and that may contain high energy fluids or compressed gases.

d) The ability to control and monitor the plant:

- The control and monitoring systems associated with the essential seismically qualified safety functions are qualified for operation from the main control room following an earthquake.
- The main control room and the secondary control area and the associated equipment are seismically qualified.
- Electrical power is supplied from a qualified electrical power system, which consists of redundant divisions of on-site power supplies (standby generators and batteries).
- Seismic monitoring instrumentation with suitable alarms are provided.
- Should the main control room become unavailable, sufficient seismically qualified monitoring and control equipment are provided in the secondary control area to control and maintain the plant in a safe state.

3. SEISMIC DESIGN PARAMETERS

3.1 Design Earthquakes

The Design Basis Seismic Ground Motion parameters for the ACR plant are given in Table 1. The peak vertical ground motion parameters are taken as 2/3 of the horizontal motion parameters for both the DBE and the SDE levels per N289.3, Reference 3. This applies to the peak ground accelerations, velocities and displacements associated with the DBE as well as the SDE.

To provide greater assurance for the ACR availability and general safety of the public and operation staff, a GDE is used as a minimum for designing all non-safety-related structures and equipment. The peak ground acceleration associated with this GDE is selected as 0.1g. This level represents one third of the DBE level and forms the basis for operator action following an earthquake such as plant shutdown and inspection.

Table 1: Design Basis Seismic Ground Motion Parameters

	Soil Site		Rock Site	
	DBE	SDE	DBE	SDE
Peak Horizontal Acceleration (g)	0.30	0.15	0.30	0.15
Peak Horizontal Velocity (mm/s)	365.8	182.9	213.3	106.7
Peak Horizontal Displacement (mm)	274.3	137.15	93.2	46.6

3.2 Ground Response Spectra

The Ground Response Spectra (GRS) used in the ACR seismic design are developed according to methods described in N289.3, Reference 3. The GRS are shown in Figure 2 for soil and rock sites respectively. These spectra are based on amplification factors associated with the 90th percentile (versus the normally used 84th percentile in other standard GRS).

For rock sites and for near-field earthquake sources, the frequency content of the GRS of Reference 3 (and other national standards such as R.G. 1.60) may be under estimated. To cater for these conditions, the control frequencies for the ACR spectrum for rock sites were changed to 14 Hz and 40 Hz from 8 Hz and 33 Hz used for soil sites. This would enrich the frequency content of the spectrum in this frequency range. This added conservatism also reflects the current state of knowledge for the nature of the Central and Eastern North American earthquakes.

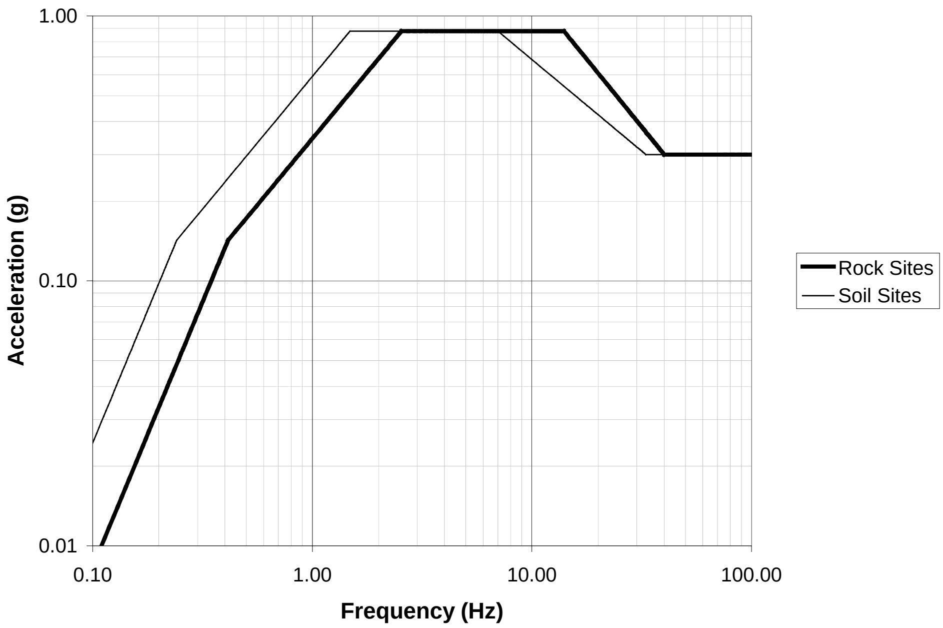


Figure 2: ACR Design Ground Response Spectra

3.3 Foundation Conditions

Potential sites for the ACR NPP were evaluated and classified into four categories; A, B, C and D. Foundation conditions were found to range from rock sites to shallow and deep soil sites. A set of nine, generic soil profiles were developed, and are being used in the seismic design of the ACR plant. Along with the fixed-base case, the nine design soil profiles provide a wide range of potential ACR site conditions.

For each soil profile, the total depth to bedrock and the variation of dynamic soil properties are established to provide conservative results. This results in an overall plant design that has an ample design margin when qualified for any specific site condition.

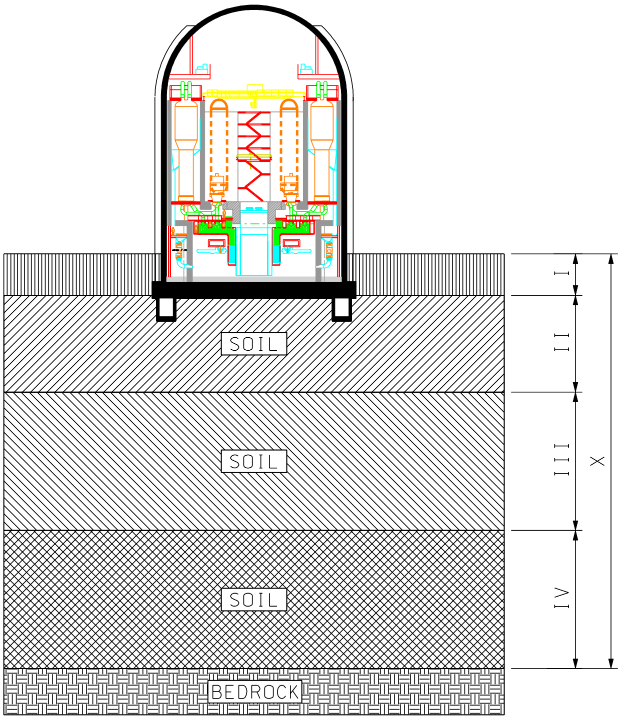
The variations of maximum shear wave velocities with depth assigned for each of the soil profiles are presented in Figure 3. The variation of both shear modulus and damping ratio with shear strain is assumed to follow the guidelines in Reference 7.

3.4 Damping Ratios

The damping ratios specified in N289 (Reference 3) for structures and components are used in the seismic design of the ACR plant. These damping ratios are more conservative than those specified in most other international standards

3.5 Stress Levels

The seismic design requirements per N289.3 (Reference 3) are more stringent than those used in other countries. For example, the ASME Level “C” stress limits are applied for the DBE case versus the Level “D” stress limits normally applied for the SSE (U.S.) or S2 (IAEA). The Level “D” stress limits are two or more times higher than Level “C” limits.



Category	A		B			C			D
X - Depth to Bedrock (m)	9.0		30.0			60.0			90.0
Soil Profile	A-1	A-2	B-1	B-2	B-3	C-1	C-2	C-3	D-1
Layer (I) = 9.0 m	590	340	590	500	340	570	330	160	160
Layer (II) = 21.0 m	----	----	760	650	430	670	380	190	190
Layer (III) = 30.0 m	----	----	----	----	----	800	460	800	230
Layer (IV) = 30.0 m	----	----	----	----	----	----	----	----	260

Figure 3: Shear Wave Velocities (m/s) and Design Profiles

4. SEISMIC DESIGN FEATURES

4.1 Separation and Redundancy

In the design of the ACR plant, emphasis has been placed on system separation and redundancy in order to ensure maximum reliability in the case of common cause events such as earthquakes. This ensures that the probability of failure of widely separated redundant systems, which have different seismic response characteristics due to the same earthquake, is extremely low. For example, there are two totally different shutdown systems: one mechanical and one chemical. Also, some safety-related systems such as the ECC, RSW/RCW and electrical systems have two redundant and adequately separated divisions each is capable of performing the system functions when required.

4.2 Seismic Qualification

Seismic qualification of the ACR structures, systems and component is accomplished in accordance with N289.3 and N289.4 (References 3 and 4). Seismic testing, analysis, or a combination of both is usually used in the seismic qualification. Design features that ensure compliance with IAEA 50-SG-D15 (Reference 8) are also considered, consistent with the CANDU plant overall safety design philosophy and economic considerations.

The effects of ageing during normal plant operation are considered for components to be qualified to DBE. Critical components affected by radiation/temperature are identified and the ageing effect on its safety functions is assessed. Many components requiring seismic testing will also require environmental testing. If the seismic qualification of a component is affected by harsh environmental conditions, the sequence of ageing, environmental test and seismic test are used. Otherwise, testing follows the sequence of ageing, seismic test and environmental test.

The dynamic characteristics of all structures, systems and components to be qualified are considered in the qualification either by analysis or by test. This includes the effects of attached conduits and cables, taking into consideration their flexibility and support characteristics, and any resulting loading imposed on the qualified component.

4.3 Seismic Design Margins

In order to assess the plants seismic design margins, a Probabilistic Safety Analysis (PSA) based seismic margin assessment is performed. Based on the results of the assessment, the plant's minimum HCLPF (high confidence low probability of failure) earthquake acceleration value is determined. Economical design modification to increase the HCLPF value are considered for implementation in the design.

4.4 Quality Assurance Plan for Seismic Design

The seismic design and qualification are based on sound assumptions, reliable analysis methods, conservative shake testing which simulates appropriate operating conditions and a thorough verification and review process. Manufacturing, construction, transportation and installation reliability are assured by strict material quality control, use of qualified workers and validated manufacturing processes, controlled packaging and transportation, thorough inspections and pre-operational commissioning which includes seismic walkdowns.

4.5 Pre-operational Seismic Walkdown

Before the ACR plant is put into operation, a plant wide seismic survey (walkdown) is carried out to provide greater confidence that the plant can withstand the DBE. A multidisciplinary team representing the owner, designers and specialists typically perform the seismic walkdown. The walkdown is performed while the station is at an advanced stage of construction and system installation (i.e. substantially completed) as an additional verification to the normal construction completion assurance process routinely implemented in the CANDU plant construction.

Findings from the seismic walkdown are tabled and recorded with recommendations to resolve them. A system of tracking the observations and their disposition is implemented. Any detected deficiency is subjected to a design review, re-analysis and/or upgrade, which may involve strengthening and modification to the design as deemed appropriate. A great deal of emphasis is placed on inspection of equipment and component anchors and supports. With the implementation of the seismic walkdown findings and any resulting improvements, the risk of failure of the as-built design due to a seismic event can be eliminated or at least is further minimized.

4.6 Seismic Instrumentation

Seismic instrumentation is provided in order to promptly determine the seismic response of the ACR nuclear power structures and equipment and permit comparison of such response with that used as the design basis.

Seismic instrumentation is provided in CANDU NPPs in accordance with the requirements of N289.5, Reference 5. The seismic instrumentation utilizes multiple types of sensor-recorders with annunciation and play-back capability provided in the main control room. The location and function of the seismic devices are selected to facilitate the determination of seismic event effects on structures and equipment via computerized analysis programs. The objective is to establish whether certain predetermined parameters such as seismic accelerations, floor response spectra and cumulative absolute velocity have been exceeded to such an extent that may warrant plant operator action. All instrumentation is qualified and provided with a back up power supply (batteries and charger).

Triaxial accelerometers, each of which measures the absolute acceleration as a function of time in three orthogonal directions coincident with major axes of analytical models, are provided typically at the free field, reactor building base slab, containment wall and the reactor auxiliary building basement. In addition, a triaxial seismic switch is placed in the reactor building. Both the accelerometers and the switches are connected to a time history analyser (central unit) located in the main control room. Additional triaxial peak accelerographs that measure the absolute peak acceleration in three orthogonal directions coincident with the major axes of the analytical models are provided at selected locations of the buildings. Audio and visual alarms are provided when the system is activated and when preset parameters are exceeded.

5. CONCLUSIONS

The CANDU NPP seismic design is based on sound principles and practices, some of which are uniquely suited to CANDU systems and components but are consistent with international codes and standards. The application of the Canadian seismic approaches including the state-of-the-art tools and techniques has ensured a robust design of the ACR NPP. The ACR NPP is conservatively qualified for a peak horizontal ground acceleration of 0.3g and for a wide range of soil/rock properties and as a result is suitable for many potential NPP sites.

The ACR seismic design philosophy and seismic design approach for meeting the safety design requirements have been reviewed. Also, other seismic design features including the pre-operational seismic walkdown and seismic instrumentation were presented. It is concluded that the seismic input parameters for the ACR plant meet current technical and regulatory requirements.

6. NOMENCLATURE

ACR	Advanced CANDU Reactor
DBE	Design Basis Earthquake
ECI	Emergency Coolant Injection (Part of the Emergency Core Coolant System)
GDE	Generic Design Earthquake
GRS	Ground Response Spectra
HCLPF	High Confidence Low Probability of Failure
HTS	Heat Transport System (Reactor Coolant System)
IAEA	International Atomic Energy Agency
LOCA	Loss of Coolant Accident
LTC	Long Term Cooling (Part of the Emergency Core Coolant System)
MSIV	Main Steam Isolation Valves
MSSV	Main Steam Safety Valves
NPP	Nuclear Power Plant
RCW	Recirculating Cooling Water
RSW	Raw Service Water
SDE	Site Design Earthquake

7. REFERENCES

1 CSA/CAN3–N289.1, "General Requirements for Seismic Qualification of CANDU Nuclear Power Plants."

2 CSA/CAN3–N289.2, "Ground Motion Determination for Seismic Qualification of CANDU Nuclear Power Plants."

3 CSA/CAN3–N289.3, "Design Procedures for Seismic Qualification of CANDU Nuclear Power Plants."

4 CSA/CAN3-N289.4, "Testing Procedures for Seismic Qualification of CANDU Nuclear Power Plants."

5 CSA/CAN3–N289.5, " Seismic Instrumentation Requirements for CANDU Nuclear Power Plants."

6 IAEA Safety Guide 50-SG-S1, "Earthquakes and Associated Topics in Relation to Nuclear Power Plant Siting."

7 Seed, H.B. and Idris, I.M., "Soil Moduli and Damping Factors for Dynamic Response Analyses", Report No. EERC 70-10, University of California, Earthquake Engineering.

8 IAEA Safety Guide 50-SG-D15, "Seismic Design and Qualification for Nuclear Power Plants."

APPENDIX A - Seismic Qualification of ACR NPP Major Systems