Seismic Qualification of CANDU-PHW Nuclear Power Plant Equipment

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Abstract
CANDU-PHW (Canada Deuterium-Uranium, Pressurized Heavy-Water reactor) nuclear power plants, whether in Canada or abroad, are thoroughly qualified to resist potential earthquakes because of the great emphasis placed on nuclear safety. CANDU Plants have been seismically qualified dynamically since the mid-1960s, with ever-increasing requirements for each new plant. The approach now employed in Canada for seismic qualification of CANDU equipment and systems is described in this paper. While many of the Canadian technical requirements, criteria, procedures, and methods are similar to those developed by the U.S. NRC (United States Nuclear Regulatory Commission), they are uniquely suited to the CANDU system. In some cases, the Canadian approach differs from that applied in other countries, and in many ways is more conservative. This paper provides typical examples to show that the CANDU equipment and systems are seismically qualified using state-of-the-art techniques and methods.

Résumé
Qu'elles soient situées au Canada ou à l'étranger, les centrales nucléaires CANDU-PHW (Canada Deuterium Uranium, réacteur à eau lourde sous pression) sont qualifiées pour résister aux tremblements de terre en raison de l'importance accordée à la sûreté nucléaire. Les centrales CANDU sont qualifiées sismiquement (méthode dynamique) depuis le milieu des années soixante, et des critères de plus en plus sévères ont été appliqués à chaque nouvelle centrale construite depuis. Cet article décrit l'approche adoptée par le Canada pour doter le matériel et la filière CANDU des caractéristiques parasismiques nécessaires à sa qualification. Bien qu'un grand nombre des exigences, critères, procédés et méthodes techniques utilisés au Canada correspondent à ceux de la United States Nuclear Regulatory Commission, ils ont été établis tout particulièrement pour la filière CANDU. Dans certains cas, l'approche canadienne diffère de celle d'autres pays et est aussi plus prudente à plus d'un égard. L'article offre des exemples typiques démontrant les caractéristiques parasismiques du matériel et de la filière CANDU obtenues grâce à l'incorporation de techniques et de méthodes à la fine pointe de la technologie.

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). The seismic design of nuclear power plants requires special consideration because of concern for the nuclear safety of the public. The CANDU seismic design philosophy is based on principles established by the Atomic Energy Control Board (AECB) of Canada. The resulting requirements and criteria to ensure the integrity and safety of structures and equipment in the event of an earthquake have been developed by the Canadian Standards Association (CSA), and published as National Standards of Canada by the Standards Council of Canada (CAN3 N289 series). The design requirements, criteria, and methods for seismic qualification of CANDU systems and equipment will be described briefly in the following sections.

Seismic Design Requirements

The CANDU plant is designed to satisfy three general safety requirements [Duff and Usmani 1984]. These requirements must be met in the event of an earthquake to minimize the radiological risk to the public:

1. Means shall be provided to shut down the reactor safely and maintain it in the safe shutdown condition as required in the event of an earthquake.
2. Means shall be provided to remove residual heat from the core after reactor shutdown.
3. Means shall be provided to reduce the potential for release of radioactive materials and to ensure that any releases are within acceptable limits in the event of an earthquake.

Keywords: CANDU-PHW, seismic qualification, seismic categories, design basis earthquake, site design earthquake, National Building Code of Canada, Canadian Standard Association, response spectrum, dynamic analysis, shake testing.

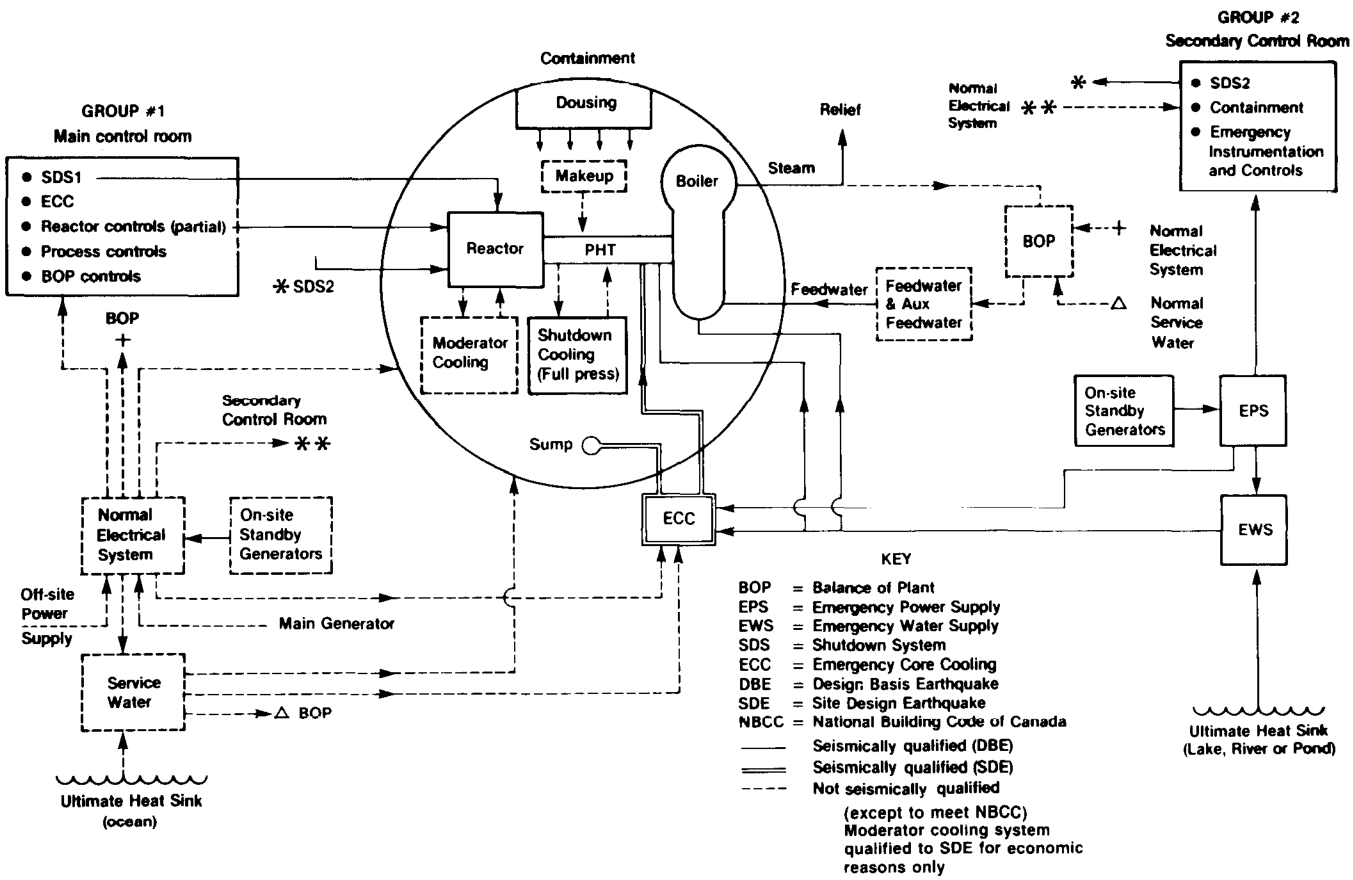

Figure 1: Seismic qualification and system separation for a CANDU 600 NPP on an ocean site.

These general safety requirements are met by seismically qualifying sufficient numbers of equipment and systems to ensure the following:

1. The reactor is capable of being safely shut down and being maintained in that state indefinitely.
2. Decay heat can be removed from the fuel during the shutdown period. As one requirement of this function, the primary coolant system pressure boundary shall not fail.
3. The containment building and associated isolation systems shall remain functional.

The major systems and structures requiring seismic qualification are shown in Figure 1. The plant systems are arranged in two independent, diverse, and widely-separated safety groups as shown.

Seismic Categories

Two categories of system components are defined [Duff and Usmani, 1984] as regards seismic qualification: category 'A' components are those whose pressure boundary or structural integrity must be maintained; category 'B' components are those which, in addition to category 'A' requirements, must also remain functional.

The particular seismic requirements for each system component usually cannot be adequately covered by the general definition of 'A' and 'B' classification. Therefore, the detailed seismic requirements for each component, including whether it is required to operate after an earthquake, or during *and* after an earthquake, are identified, and the components are designed accordingly.

Design Earthquake Levels – Definitions

The Canadian National Standards CSA-N289 require that nuclear power plant (NPP) structures and systems important to safety meet more restrictive design requirements than those imposed by the National Building Code of Canada (NBCC). CSA-N289.1 defines two levels of earthquake safety: 1) 'The Design Basis Earthquake (DBE),' an engineering representation of potentially severe effects at the site of earthquakes, applicable to the site, that have sufficiently low probability of being exceeded during the lifetime of the plant; and 2) 'The Site Design Earthquake (SDE),' defined as 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 (with a minimum level of 0.03 g). The SDE is always a more probable event, and therefore has a lower intensity than the DBE. Only one earthquake, the SDE or the DBE, is assumed to occur during the design life of the NPP. Other structures and systems shall be designed to meet at least the NBCC, or equivalent, in order to ensure a minimum degree of resistance against collapse or failure, to mitigate the effects of earthquakes on nearby safety-related structures and systems.

Acceptance Criteria

The seismic qualification acceptance criteria for CANDU system components are as follows: strength, deformation, stability, fatigue, function.

Seismically-induced 'fatigue' is a special consideration in the design of CANDU-NPPS, especially for highly-stressed, pressure-retaining components and piping systems. It has been shown [Duff and Heidebrecht, 1979] that, for critical equipment, the earthquake fatigue effect is the equivalent of up to 25 cycles at the maximum amplitude or stress level. The criteria 'function' must be confirmed by testing, as all of the other acceptance criteria can be evaluated analytically. It is for this reason that important components, such as shut-off rods, must have their moving parts tested under simulated earthquake conditions [Kuroda and Duff, 1982].

Seismic Design Guidelines

The following guidelines [Usmani, 1986] are applied in CANDU Seismic Design:

- The random failures of seismically qualified components and structures coincident with an earthquake are incredible, and therefore need not be considered in the plant design.
- The plant design considers the most adverse effect of the non-qualified systems on the qualified systems.
- The instrumentation and control associated with the essential safety function of a system shall be qualified to the same level and category as the system.
- Cables, cable trays, conduit, and their supports for a system required for safe operation shall be qualified. They shall be routed separately from unqualified cable pans to avoid damage from such equipment.
- Fire protection systems shall be designed to avoid damage to seismically qualified systems through falling or spurious operation.
- An analysis, test report or other justification of seismic capability shall be prepared for all seismically qualified equipment and structures, to demonstrate that the safety requirements have been satisfied.
- All systems and structures of the plant shall be designed to comply with the latest codes.
- Site surveys [Duff and Stevenson, 1984] shall be conducted at an advanced stage of construction and system installation. This is to determine, both by inspection and by *ad hoc, in situ* testing, that the as-built, as-installed condition of the nuclear plant will be in a safe state during and following a severe earthquake.
- All control operations that must be completed within 15 minutes after an earthquake shall be automated.
- All monitoring and manual control functions required shall be exerciseable from a seismically qualified control area.
- All qualified systems and components shall be designed and located to minimize their exposure to hazards resulting from failure of unqualified systems. This shall be done by locating the majority of seismically qualified components in an area where surrounding components are qualified.
- In addition, and where necessary, the exposure to hazards shall be minimized by the use of barriers, or by maintaining sufficient distance between qualified and unqualified components.
- As a minimum, supports, anchors, bracing, etc., shall be designed for an earthquake (DBE or SDE, as applicable), unless it has been shown that the consequence of failure would not constitute a safety hazard.
- The Main Control Room (MCR) shall be designed to ensure operator safety during and following an earthquake. The Secondary Control Area (SCA), including the access routes from the MCR to SCA, shall be seismically qualified for post-earthquake plant operation.

Canadian Approach vs. Others – Highlights

As befits an active participant in the NUSS program of the IAEA, Canada's seismic design criteria meet [Duff and Usmani, 1984] the requirements of the IAEA Safety Code on siting, 50-C-S, the IAEA Safety Guide on earthquakes with respect to nuclear power plant siting, 50-SG-S1, and the IAEA Safety Guide on seismic analysis and testing, 50-SG-S2.

Table 1 is derived from the IAEA criteria, where only two levels of earthquake, S_2 and S_1, are specifically defined. The S_2 is comparable to the Canadian DBE, whereas the S_1 is more in line with the Operating Basis Earthquake (OBE), frequently applied in other countries. Table 2 illustrates the same information in terms of the Canadian seismic design criteria. The specific design requirements are drawn from CSA, ASME, and the NBCC Standards. In general, these design requirements differ from those used in other countries; for example, the ASME level 'C' stress limit [ASME, 1983] is applied for both the DBE and SDE, whereas the U.S. NRC permits stresses for the SSE (Safe Shutdown Earthquake, corresponding to the DBE or S_2) to meet the level

Table 1: IAEA Earthquake Design Levels

System category	*Earthquake level*	*Design requirement*	*Plant status (post-earthquake)*
Major process and safety systems	S_2 (DBE)	Nuclear Code	Serviceable
Safety-related systems	S_1 (OBE)	Nuclear Code	Operable
Other systems	$\leq S_2$	National Building Code	Non-collapse

Table 2: Canadian Earthquake Design Levels

System category	*Earthquake level*	*Design requirement*	*Plant status (post-earthquake)*
Reactor and reactor building major process and special safety systems and their supporting structures	DBE	CSA-N285 -N287 -N289 and ASME level 'C' stress	Safe and serviceable
Emergency core cooling system	SDE	CSA-N285 -N289 and ASME level 'C' stress	Safe and serviceable (following LOCA)
Other systems and structures	NBCC	National Building Code of Canada	Non-collapse

'D' limit. The design of a system to level 'C' of the ASME Code, Section III, for the DBE (S_2), is the equivalent of designing for at least six, S_1-level earthquakes of one-half the S_2 intensity, in terms of shakedown and fatigue damage [Duff and Heidebrecht, 1979].

The Operating Basis Earthquake (OBE) as such is not applied in Canada. This is entirely in keeping with the IAEA Siting Guide. As the Canadian approach applies the DBE to all structures and systems essential to ultimate plant safety, the only requirement for an OBE, will be economic reasons such as plant operation and availability. For these reasons, all non-safety-related structures and systems are designed to the NBCC, using more conservative methods than called for by that code, and cascading effects are minimized. The proof of the inherent capability of CANDU NPPs to continue operating through low-level earthquakes is borne out by the fact that there have been no failures of any operating CANDUs, including some in an advanced stage of commissioning, during actual earthquakes estimated to range from 0.01 to 0.1 g.

Seismic Qualification Methods and Selection

Seismic Qualification Methods

Seismic qualification can be demonstrated by analysis, testing, and a combination of analysis and testing. Of the above methods, full dynamic analysis is the most common and acceptable.

Testing is necessary when a system or component is too complex to model and analyze reliably. Testing is especially important when it is necessary to demonstrate that the equipment can perform a function reliably (electrical or mechanical) during and / or following an earthquake.

Testing may be performed at a low level of excitation for obtaining suitable dynamic characteristics to enable a meaningful dynamic earthquake analysis to be carried out. It may also be used to confirm analytical results for increasing the level of confidence. Testing may also be performed on scale models where full-scale testing is out of the question or would be performed too late to permit necessary changes to be made.

Seismic qualification may be claimed where a piece of equipment has been selected that is identical with, or similar to equipment that has already been seismically analyzed or tested for similar conditions, or has safely survived an actual earthquake of equal severity under equivalent operating conditions.

Analytical Methods

The analytical methods that are available are the time-history method by direct integration, the time-history method by modal superposition, the response-spectrum method, and the equivalent static-load method.

The time-history methods are the most rigorous and costly. These are used in limited cases where other methods yield unacceptable results. A suitable time-history of the required DBE, either at ground level or at floor level, is used as seismic input.

The response-spectrum method is the most common, as well as being the cheapest to apply. The Ground Response Spectrum (GRS) is used to represent, on a mode-by-mode basis, the response of the building or other structure to ground motion, while the Floor Response Spectrum (FRS) is used to determine, in a similar manner, the response of equipment. Proper care must be taken to determine the responses in each mode and in each direction of earthquake excitation, and to combine the results appropriately.

The equivalent static-load method is a simplified, but usually conservative way of determining and applying horizontal seismic design loads to simple systems or components without having to perform a full-scale dynamic analysis.

Typical Examples

Seismic qualification of CANDU equipment and components is established by analysis, testing, and combination of analysis and testing, as appropriate. Some typical equipment and their qualification methods are described briefly in the following section.

A Heat Transfer System (HTS) pump (Figure 2a) is required to maintain pressure boundary integrity and must remain free wheeling during and after a DBE. This

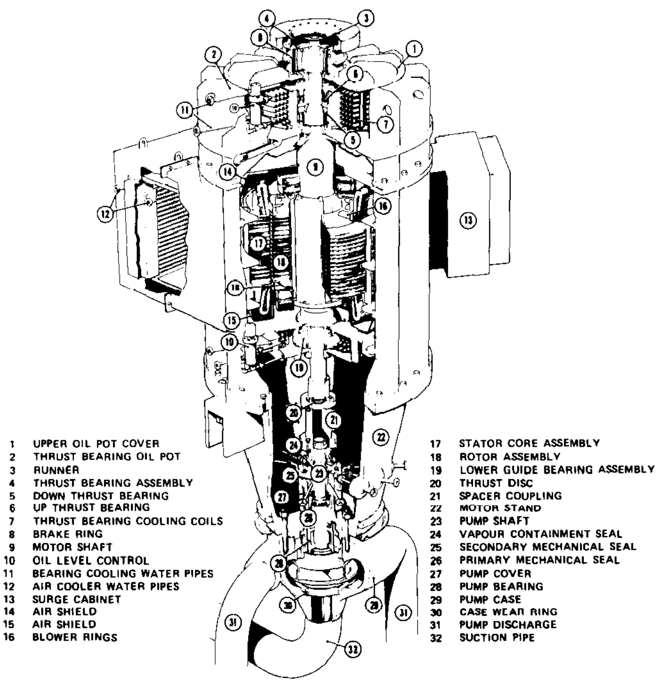

Figure 2a: Heat transport system pump.

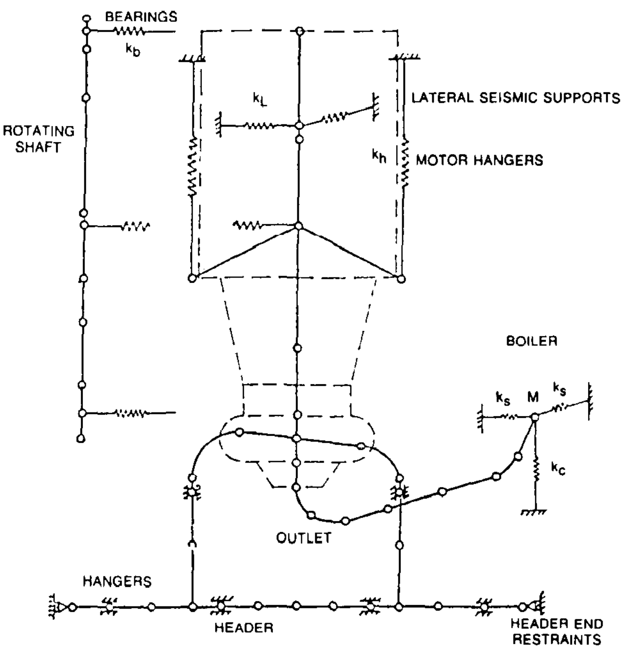

Figure 2b: Schematic dynamic model of pump.

is demonstrated by dynamic analysis, along with testing of parts such as the bearings and the motor. A typical dynamic model of the pump and the rotor-bearing system is shown in Figure 2b. From the analysis it is shown that, due to seismic-loading, the bearing does not fail, the clearance between the rotor and the stator does not close, and the structural integrity of all components is maintained.

A steam generator (Figure 3a) is required to maintain

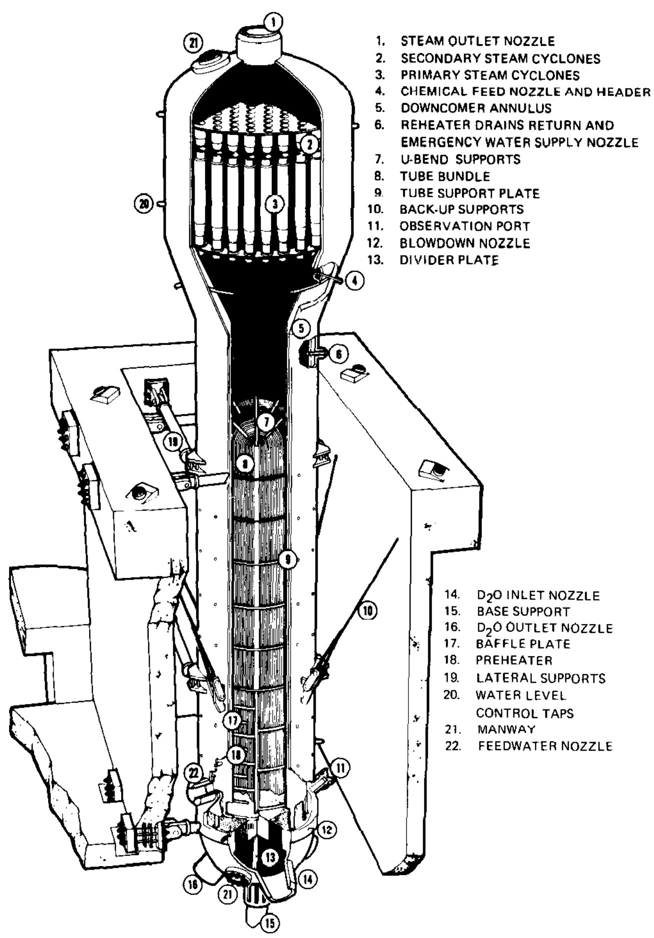

Figure 3a: Steam generator for 600 MW(e) NPS.

heat rejection capability and the pressure boundary integrity. This is demonstrated by dyanamic analysis. The typical model (Figure 3b) includes all the internal components. The dynamic properties, such as damping and stiffnesses of some components, are established by testing.

Piping systems are qualified by extensive dynamic analysis, taking into account both inertia and seismic anchor movements. Multiple-support excitation techniques are applied, when necessary, to cut down the over conservatism of the envelope Floor Response Spectrum (FRS) approach. A typical model of CANDU feeder piping is shown in Figure 4.

Valves are seismically qualified by analysis and testing. Safety related valves, such as the quick-opening valve in the second shutdown system, are shake-tested to demonstrate operability. Other valves are tested by simulating the worst seismic loading by an equivalent side-load test.

The fuelling machine (Figures 5a, 5b) is qualified [Banwatt *et al.*, 1985] by dynamic analysis. The dynamic characteristics, non-linear effects, and model verifications are based on extensive dynamic test results.

Control and instrumentation equipment is seismically qualified by shake-testing. The stand-by diesel

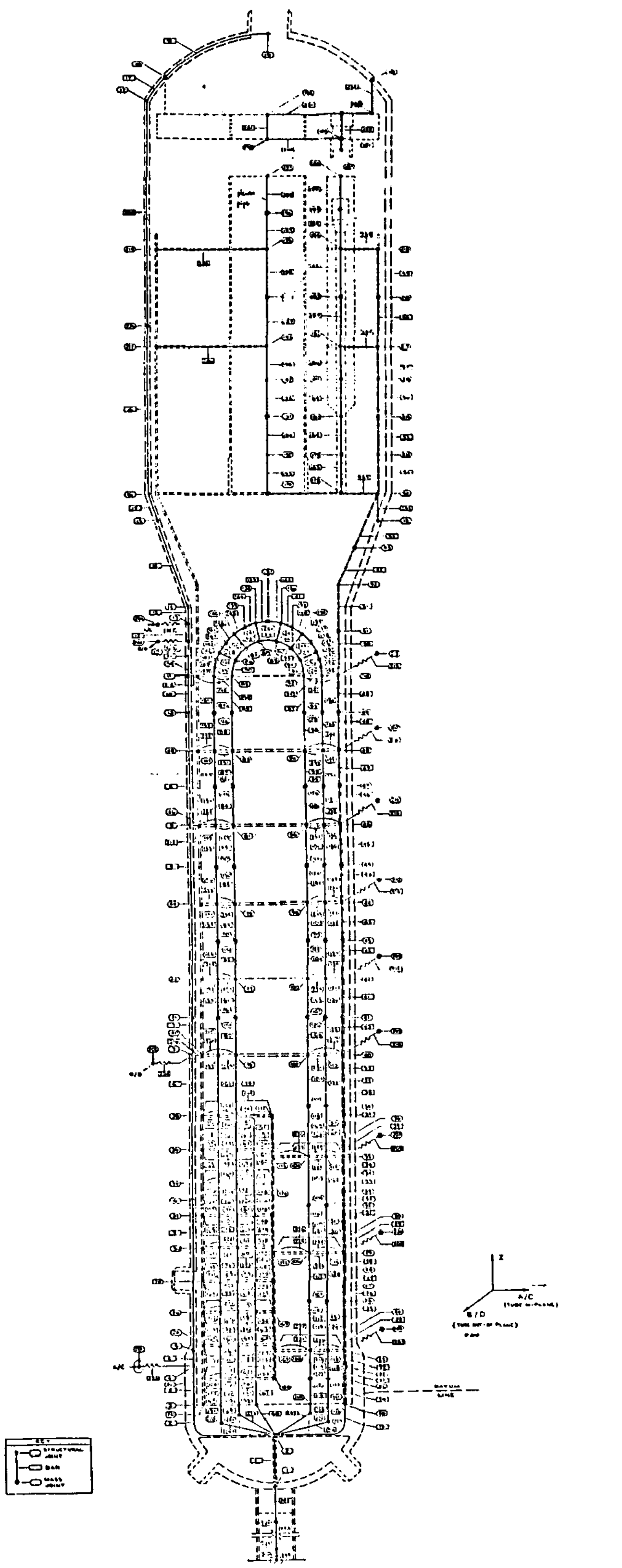

Figure 3b: Mathematical model of steam generator and its internals.

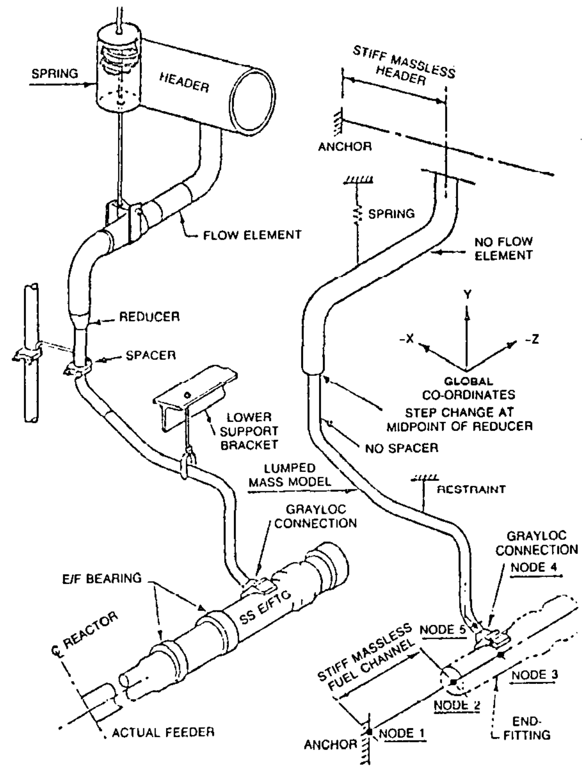

Figure 4: Analytical model of feeder.

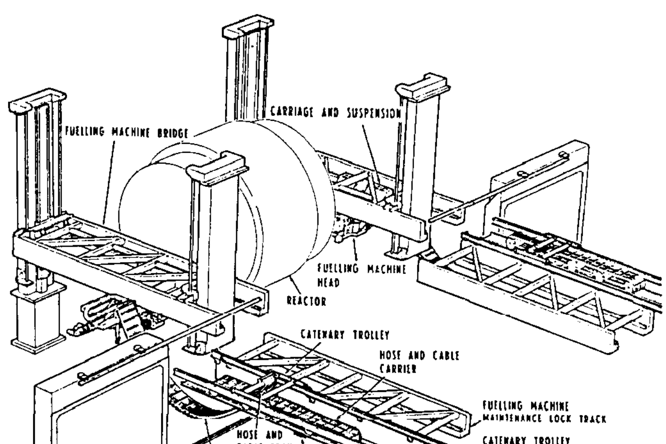

Figure 5a: Fuelling machine.

generators (Figure 6) have been qualified by shake-testing as well.

The core, including the shut-off rod mechanisms, have been seismically qualified [Kuroda and Duff, 1982] by testing full and partial scale models (Figures 7a, 7b) under very severe seismic motions simulated on a shaker table.

Conclusion

The Canadian seismic design approach and methods for seismically qualifying the CANDU-PHW nuclear power

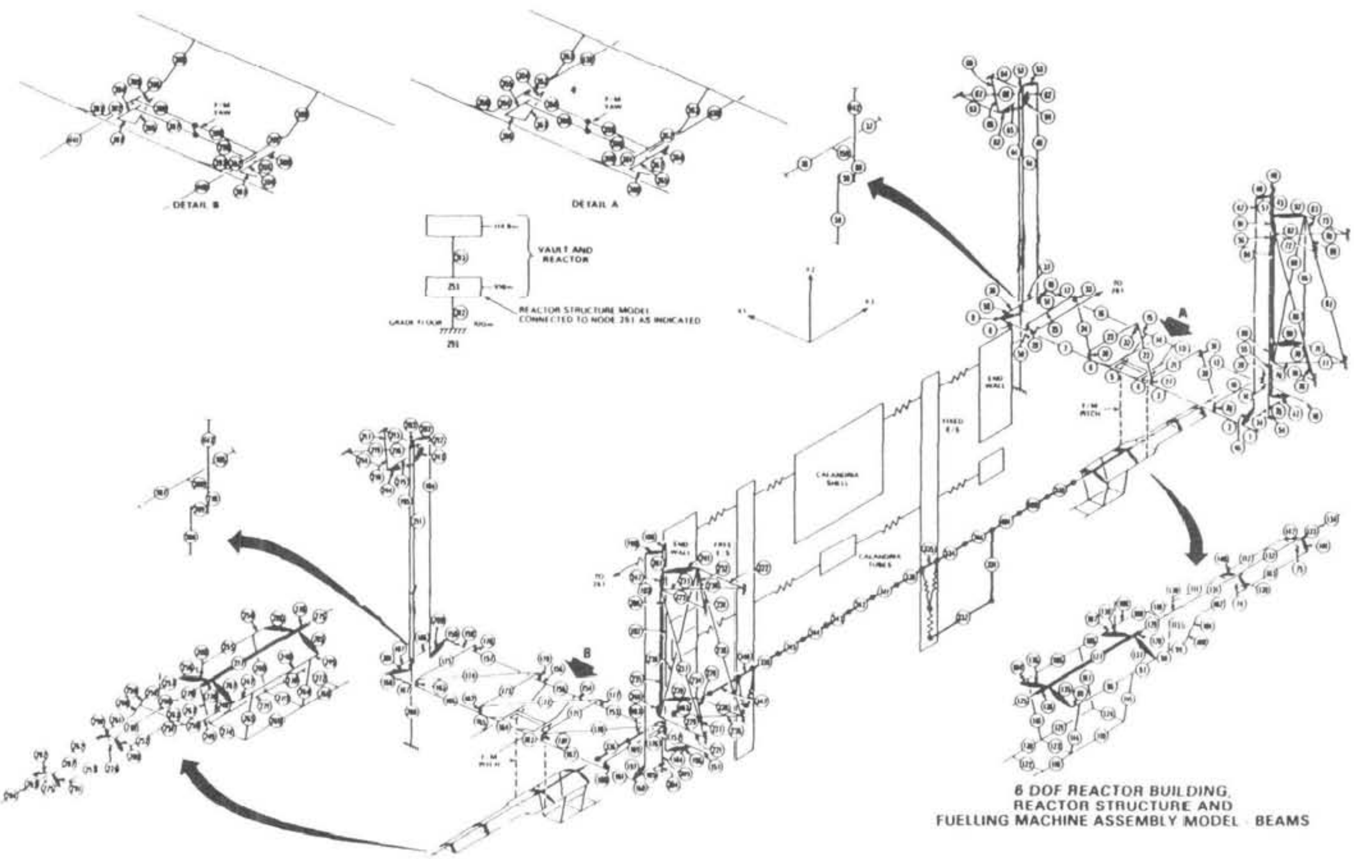

Figure 5b: Fuelling machine dynamic analysis model.

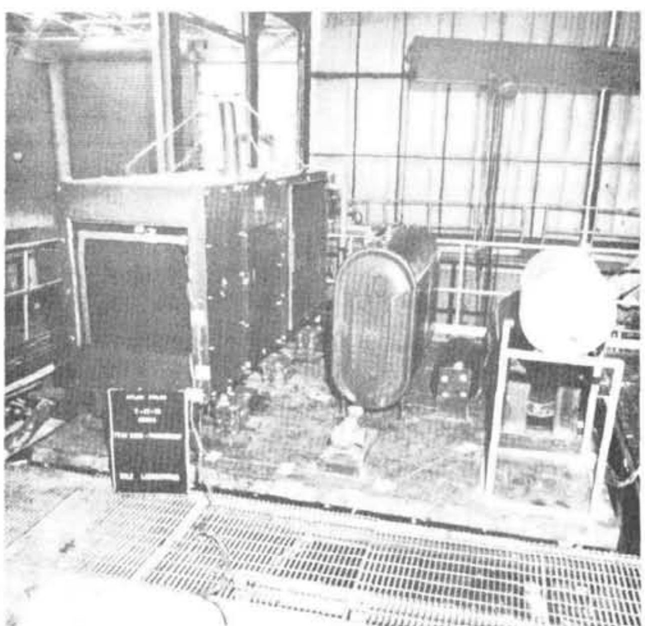

Figure 6: Shake-up test setup EPS diesel generator and accessories.

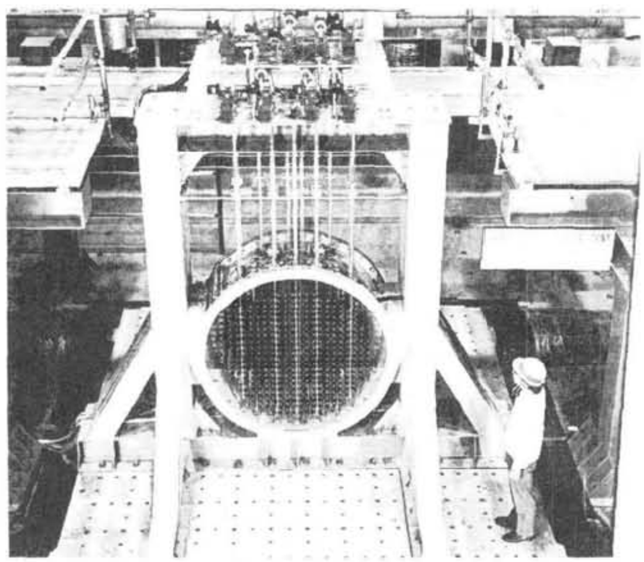

Figure 7a: CANDU core seismic test 1/5 scale model.

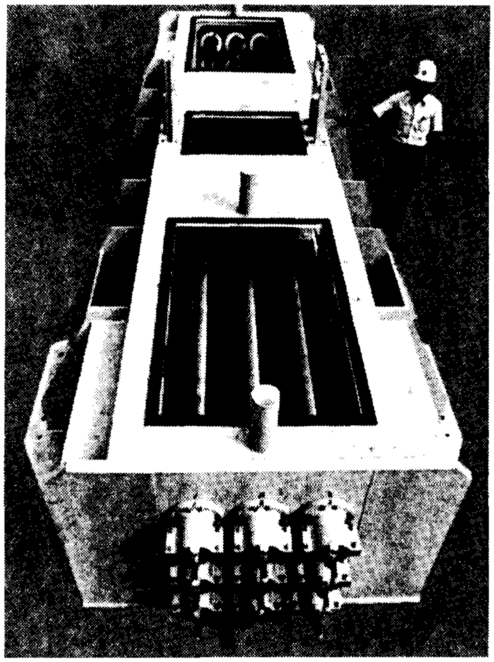

Figure 7b: CANDU core seismic full-scale partial model.

plant's system and equipment are unique in some respects, especially in terms of design conservatism, pre-operational inspection, and avoidance of any need to cater explicitly for an operating basis earthquake. By designing essential structures and systems to at least the earthquake requirements of the National Building Code of Canada – and all areas important to safety to the low-probability DBE – using conservative criteria, CANDU nuclear power plants are capable of safely surviving any earthquake they are likely to experience during their operating lifetime. The CANDU equipment and systems are seismically qualified using state-of-the-art technique and methods.

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