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SURVEY OF PAST BASE ISOLATION APPLICATIONS IN NUCLEAR POWER PLANTS AND CHALLENGES TO INDUSTRY/REGULATORY ACCEPTANCE

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ABSTRACT

Seismic base isolation provides many benefits that can facilitate the standardization of future nuclear power plant structures and equipment while reducing the initial/life-cycle cost and construction schedule. This paper presents a survey of past seismic base isolation applications and studies related to nuclear applications and provides a discussion of the challenges that need to be overcome to gain industry and regulatory acceptance for deployment in future US nuclear power plants. Issues related to design, codes/standards/regulations, procurement, and construction, have been identified.

Keywords: Seismic Base Isolation, Nuclear Regulation, Codes and Standards, Seismic Gap, Isolator Testing, Quality Assurance

1. INTRODUCTION

Seismic isolation is a mature technology that has already been applied to many infrastructure and mission-critical facilities. There are many potential advantages of deploying seismic base isolation for future nuclear power plants. The most important advantage is that the overall reliability and safety of nuclear plants can be improved. This is because the design of the major plant equipment and structures can be standardized irrespective of the design ground motion; i.e., variation in the design seismic acceleration levels can be accommodated by making adjustments to the isolation system. Such standardization of equipment and superstructure in base isolated plants will cut costs and design/construction schedule for new nuclear power plants. Further, base isolation will enable decoupling of design development for equipment, piping, and components due to the use of generic in-structure response spectra associated with the standardized plant. Also, due to its superior seismic performance capability against the design basis earthquake as well as a beyond-design-basis seismic event, the plant safety margin will be improved (compared to a conventionally designed plant).

Application of base isolation will also help overcome the following emerging seismic issues:

- US Nuclear Regulatory Commission Regulatory Guide 1.165 (NRC, 1997) requires that the seismic design of nuclear plants be based on a probabilistic seismic hazard assessment (PSHA) for a 100,000-year return period. For many existing nuclear plant sites, especially in the central and eastern US (which are the likely candidates for next-generation units), the associated design ground motion is quite high (Carrato and Litehiser, 2005) such that construction of a new nuclear power plant could become exorbitantly expensive.
- For the prospective sites located within the central and eastern US, recent seismic hazard studies have confirmed increased high-frequency content in the design spectrum (and some collateral increase in the medium range frequency content). While the increase in high frequency content has a relatively small significance for the design of structures, the full extent of this problem has not yet been conclusively studied. Consideration of wave incoherency effects results in some benefit (Ostadan, et al, 2005); however, regardless of the structure size, base isolation will further reduce the shaking intensity transmitted to the superstructure.

The potential advantages of seismic base isolation notwithstanding, the US nuclear industry and regulatory agencies must proceed with caution by studying its past experiences with base isolation and ascertain how the currently available (and improved) isolator technologies can be justified for such a mission-critical application. In particular, the unique requirements for service in the nuclear industry must be properly carefully addressed prior to deployment. To this end, the authors of this paper have been canvassing various isolation experts, regulators, utility companies, equipment suppliers, and isolator vendors to develop a consensus and a strategy for eventual application of base isolation to nuclear power plants.

2. PAST STUDIES/APPLICATIONS OF BASE ISOLATION TO NUCLEAR FACILITIES

In the nuclear industry, there have been many past instances of either full deployment of base isolation or development of appropriate specifications to enable such deployment. This paper will discuss the lessons/perspectives gained from such applications and studies.

There are currently six seismically isolated Pressurized Water Reactor (PWR) units: four in France and two in South Africa. At the Cruas plant in France, each of the four units has been constructed on 1,800 neoprene pads measuring 500 by 500 by 65 mm. The seismicity at this site is moderate, with a safe shutdown earthquake (SSE) design acceleration of 0.20g. In Koeberg, South Africa, two units are isolated on a total of 2000 neoprene pads measuring 700 by 700 by 100 mm. In this case the SSE design acceleration is 0.30g. The pads are outfitted with flat sliders on the top surface, consisting of a lead-bronze alloy lower plate and a polished stainless steel upper plate. The sliding feature was implemented so that the lateral force transmitted to the reactor vessel is limited to the frictional resistance of the sliding interface (nowadays the Friction Pendulum System (FPS) method is widely preferred over flat sliders as it has a built-in re-centering ability without requiring the use of any special springs, as in case of flat sliders).

The long-term behavior of the isolators used in France and South Africa has been one of the issues that makes them unsuitable for an application to a US nuclear facility. Neither type of bearing used in France or South Africa are utilized nowadays for a seismic isolation project in the United States. Specifically, the synthetic rubber Neoprene used in the French isolators has been known to age-stiffen (changing the properties of the isolation system) and the bimetallic interface used in the South African isolators is now banned from use in seismic bearings because the mechanical properties of such interfaces can change substantially with time. Currently, there are significantly better types of isolation systems available (with re-centering capabilities) and the associated design/testing rules have been increasingly well codified and streamlined (e.g., ASCE, 2002). The past base isolation applications (in France and South Africa) are considered outdated in terms of the current state-of-the-art.

The Japanese government has sponsored various initiatives over the last 15-years to evaluate the viability of base isolation technology for nuclear facilities. In 1997, the Central Research Institute of Electric Power Industry (CRIEPI) issued appropriate guidelines for application to Fast Breeder Plants and Light Water Reactors. Although there are currently no seismically isolated nuclear reactors in Japan, these guidelines make them a possibility. Work has also been underway in Japan for applying seismic isolation to the International Thermonuclear Experimental Reactor (Fujita, 1997).

In 1998-1999, AECL, a Canadian NSSS supplier, actively explored and advocated the use of base isolation during its bid for the (now abandoned) Akkuyu nuclear power project in Turkey. Incidentally, data available from an AECL study (AECL, 1996) indicated that Teflon, used in sliding-type isolators, can withstand radiation dose levels as large as one Mrad without much performance deterioration. More recently, AECL's participation in the analytical research being conducted by the researchers at the University at Buffalo (Whittaker, et al, 2005) is helping quantify the benefits provided by base isolation.

Westinghouse also conducted a study of horizontal base isolation for its AP600 plant during the nineties (Westinghouse, 2004). This study was directed primarily to determine if the AP600 standard design could be applied to sites in Japan where the design ground motion exceeds the 0.30 g design basis for the AP600. It was felt that the AP600 and AP1000 plants needed more commercial success before applications (with or without seismic isolation) to sites with higher design ground motion were considered.

In the US, the Department of Energy (DOE) had sought to use the base isolation technology for the nuclear island facilities of its Advanced Liquid Metal Reactor (ALMR) project in order to improve safety and to allow the development of a standard design for varying regions of seismicity. The prototype ALMR design incorporates 66 high damping rubber bearings. Prototypes of these bearings have been tested extensively (Tajirian, 1990 and Clark, et al, 1995). The DOE has also been developing a Sodium Advanced Fast Reactor (SAFR), which incorporates seismic isolation. The prototype design is supported on 100 elastomeric isolators. Reduced scale isolators have been tested to verify their performance (Aiken, 1989).

Recently, INEEL and Bechtel studied the application of base isolation to a US nuclear power plant. Discussions with the utilities and NRC staff (NRC, 2004) indicated that any move to implement seismic base isolation on a nuclear power plant will require an extensive scrutiny of issues such as long-term behavior of isolators, in-service/pre-service inspection and testing of isolators, and the basis for choosing an adequate isolation gap (based on some beyond-design-basis consideration).

Most US suppliers of advanced light water reactors (and others wishing to enter the US market) have based the design of their plants on a peak ground acceleration of 0.30 g, with some ad hoc modification to the response spectrum shape specified in Regulatory Guide 1.60 (NRC, 1973) to reflect increased high frequency content encountered in the central/eastern US regions. They are hoping that the PSHA-based site-specific spectra for prospective sites can be enveloped by these presumptive design spectra. Recent early site permit studies however indicate that such hope may be misplaced because of the exceedances in both medium and high frequency ranges. The authors have generally found that while there is a desire to cautiously approach the base isolation solution, the biggest hurdle so far appears to be a collective inertia and/or lack of sufficient knowledge about the state-of-the-art practice, which prompts utilities and NSSS suppliers to keep choosing conventional design options.

3. DESIGN CONSIDERATIONS FOR BASE ISOLATED NUCLEAR POWER PLANTS

Several design considerations need to be factored in when designing seismic isolation systems for a nuclear power plant.

Selection of Isolation Criteria: While the seismic response consideration generally does not control the designs of nuclear power plant structures in low to moderately seismic areas (radiation shielding, accident loading, etc., often govern the design), the same is not necessarily true for many of the major equipment, piping, and other safety-related commodities. It is envisioned that the nuclear steam supply system (NSSS) equipment suppliers could specify the required response spectra (RRS) for their equipment based on known equipment fragility characteristics and/or economic design considerations. Unfortunately, NSSS suppliers generally tend to have a “linear" design process in that the discipline(s) responsible for design of equipment and its supports simply utilize the floor response spectra provided by the civil/structural discipline. The potential benefits of seismic isolation are not understood/realized in such a scheme unless the RRS is too high for the equipment designers to deal with. For base isolation to become an accepted practice, the NSSS suppliers and other major equipment vendors will need to play a critical role in helping develop sensible isolation criteria.

Isolation Diaphragm: To minimize the number of flexible couplings for systems that traverse between isolated and non-isolated facilities, it is preferable to isolate the entire nuclear island (i.e., all structures other than the balance of plant facilities) using a common diaphragm to support the associated structures above the isolators. Use of a common diaphragm will avoid large relative displacements between the superstructures of the various nuclear island facilities. Use of a common mat with large footprint will also result in increased benefit from wave incoherency effects. Having a large common mat may be undesirable because of the uneven mass/stiffness distribution and the differing base slab thickness requirements for the various nuclear island structures (including their internals). These factors pose difficulties from the standpoints of ease of construction and/or achieving a relatively uniform distribution of seismic demand on individual isolators. On the other hand, using separate diaphragms for each nuclear island structure will increase cost as well as schedule complexity, factors that will need to be weighed against the alternative of using a common diaphragm. For a large common mat with irregular mass and stiffness distribution, the use of prestressed isolators and appropriate isolator placement strategies will help overcome isolator uplift/overturning problems.

Longevity and Service Conditions: The next generation of power plants will likely be licensed for 60-year operation or more. Accordingly, the isolation system will need to have the requisite long-term reliability in a potential radiation environment and elevated temperatures (after a loss of coolant accident [LOCA] or main steam break event). If aging is shown to result in a diminished ability to provide seismic isolation, then it would be necessary to carry out an "end-of-the-life" analysis, considering appropriately conservative values for isolator properties. Also, appropriate in-service surveillance and maintenance for each type of isolation system will need to be performed to assure continued reliability. Among the common types of isolators available commercially, the friction pendulum (FP) isolators is expected to demonstrate relatively inert and durable characteristics. In any case, appropriate "end-of-life" isolator properties will need to be used to design for long-term performance.

Isolation/Expansion Joints: Balance of plant (BOP) systems, including major systems such as main steam and feedwater, that traverse from non-isolated facilities will need to be fitted with special flexible expansion joints that can accommodate the relative movements between the facilities. These relative movements are expected to be in the neighborhood of 1 to 2 feet (especially in high seismic areas), a significant challenge for the design of isolation joints. The procurement/design of these specialty items will need to be planned in advance with close dialog and coordination between the parties involved. In some ways, the viability of seismic base isolation and the choice of a particular type/layout of isolaton system itself will depend on the industry's ability to procure appropriate expansion joints for isolating the BOP systems. Therefore, an active effort will be needed to ensure that appropriate isolation joints are available (or can at least be manufactured economically) for high pressure/temperature pipes with large diameters.

Effects of Vertical Excitation: Response to vertical excitation is an important design consideration in a conventionally designed plant. For base isolated nuclear plants, the effects of simultaneous horizontal and vertical shaking needs to be studied to adequately capture the influence of vertical acceleration. Design of packaged isolators that can provide isolation from both horizontal and vertical seismic accelerations is also of interest. The isolation industry has been pursuing this challenge for a long time; however, the advent of a commonly accepted packaged isolation system has so far been elusive.

Specification of Beyond-Design-Basis Criteria: The NRC may stipulate some "beyond-design-basis" criteria in terms of increased hazard (i.e., higher ground motion) or some safety performance goal (i.e., limiting the deformation of plant SSCs). In the absence of any NRC-mandated criteria, the A/E and Owner will need to select suitable criteria. Whether the beyond-design-basis earthquake criteria are established by the Owner or dictated by an NRC regulation, the isolation system will need to be appropriately designed to meet the associated requirements. This will also have an impact on the capability of the isolation joints in the isolation system and the required seismic gap. As a remote possibility, springs/dampers may need to be provided to cushion the impact forces transferred when the limit of sliding travel is exhausted.

4. QUALITY ASSURANCE/QUALITY CONTROL AND CODE/STANDARD CONSIDERATIONS

Several QA, testing, and code/standard considerations need to be factored in when procuring materials and services for seismic isolation systems to be used in a nuclear power plant.

Procurement Issues: The U.S. Nuclear Regulatory Commission (NRC) will first need to approve (either generically or on a case-by-case basis) and subsequently regulate the use of isolation systems in U.S. nuclear power plants. For safety-related applications, the isolators will need to be procured in accordance with the QA/QC requirements of 10 CFR 50, Appendix B. Adapting to these requirements will be a major issue for isolator producers, as they are not accustomed to the kind of procedural rigor common in the nuclear industry (i.e., the QA/QC requirements associated with the design, testing, manufacturing, shipping/handling, and installation). Owing to the scale of each nuclear power plant project and the potential market size, the isolation industry will also need to gear up for adequate production capabilities in terms of isolator sizes, load-carrying capacity, and production rate.

It will be necessary to canvass suppliers to maintain open lines of communication and to help them prepare for the challenges that lay ahead. Notwithstanding the difficulties, it is noted that the isolation community has experienced increasing quality, testing, and peer review requirements imposed by code bodies and customers (e.g., DOE projects for ALMR and SAFR projects and California Department of Transportation) that have used isolation systems for numerous mission-critical facilities over the past one and a half decade. As is customary in non-nuclear applications, it is expected that a third party review, conducted by independent experts, will also be required for nuclear applications in order to ensure quality design and procurement.

In the area of testing, the following issues will need to be addressed:

- *Types of Tests:* Some tests will be isolator-specific (e.g., characterization of friction behavior for sliding isolators, scragging for rubber-based isolators), while others will be generic (e.g., effect of long service, effects of temperature/radiation exposure)
- *Timing/Frequency of Tests:* During the design/production phase, a protocol will need to be developed for qualification testing and in-production testing. Prior to deployment and during service, a protocol will be needed for pre-service and in-service inspection, testing, and maintenance requirements.

Applicable Codes/Standards: Many US codes and standards include technical requirements pertaining to design and testing of base isolation systems (Whittaker, et al, 2005). Barring the ASCE 4-98 standard (ASCE, 1998), the rest of such documents are geared toward non-nuclear applications. This notwithstanding, many of the requirements from the various codes/standards can be adapted/modified to establish appropriate design criteria for a base isolated nuclear power plant. An industry-wide initiative (involving the NRC) will be needed to develop a suitable standard/design guide for this purpose. Following is a (partial) list of currently available codes/standards/specifications:

- *ASCE 4-98:* “Seismic Analysis of Safety-Related Nuclear Structures and Commentary.” Section 3.5.6 of this document provides the analysis requirements for seismic-isolated structures; the NRC does not presently endorse this section. The authors are working through the ASCE 4 standard committee to significantly revise this section (including ground motion time history requirements). It is expected that the next version of ASCE 4 will serve as a platform for wider acceptance of seismic base isolation.
- *ASCE 7-02:* “Minimum Design Loads for Buildings and Other Structures.” Section 9.13 of this standard contains provisions for seismically isolated structures based on the NEHRP 2000 document (FEMA, 2001). These provisions are not intended for nuclear power facilities (although a lot of relevant guidance can still be derived).
- *National Earthquake Hazard Reduction Program (FEMA, 2004):* Chapter 13 of this document provides the most current requirements for design of base isolated structures. The latest NEHRP provisions have been adapted in the upcoming revision of ASCE 7. Note that the provisions of this document are also not intended for nuclear power facilities.
- *NIST Report NISTIR 5800 and New ASCE Standard for Testing Seismic Isolation Systems:* In 1996 a committee was formed by the American Society of Civil Engineers (ASCE) to develop code provisions for testing seismic isolation systems. The committee used as a resource document an earlier guideline on testing developed at the National Institute of Standards and Technology (NIST Report NISTIR 5800). The standard will include procedures for basic property testing, prototype testing, and quality control testing of both elastomeric and sliding isolation systems.

The above-mentioned documents address both design and testing issues for isolation systems. With active industry involvement, the material from these documents can eventually lead to appropriate topical reports and/or regulatory guides (which may also include additional guidance/provisions for testing protocol, QA/QC requirements, and isolation joints for BOP systems). Such a progression toward regulatory acceptance is key to successful deployment and will require a collective effort on the part of the nuclear industry, the isolation industry, and the regulatory community.

5. CONSTRUCTION CONSIDERATIONS

Application of base isolation to nuclear power plant structure(s) will involve several challenges with regard to planning, scheduling, and execution. On the whole, base isolation is expected to reduce the overall schedule because the design of the superstructure, major equipment, and piping can be significantly standardized. Some of the construction challenges are discussed below:

Isolation Diaphragm: A common isolation diaphragm for containment plus auxiliary building will present a construction challenge because of its size and expected thickness variations. Thickness changes in the diaphragm can be minimized, albeit at some increase in concrete/rebar quantities. A cost-benefit analysis will need to be performed to evaluate the increased quantities versus the ease of construction (and the expected schedule expediency). Close and early coordination between the design and construction teams will be needed to reach the right decision in this regard. The option to employ separate diaphragms/foundations for the nuclear island structures is deemed preferable from the construction standpoint; however, it likely will entail some adverse schedule and cost implications (i.e., the additional cost to procure an increased number of BOP isolation joints).

Adequate headroom between the diaphragm and the foundation will be needed to permit easy access to isolators for inspection, maintenance, surveillance, and potential removal for in-service testing. Another issue to be addressed is the design concept for the tendon gallery of the prestressed concrete containments. It is likely that the tendon gallery would become a part of the isolation diaphragm, thus requiring local thickening of the diaphragm.

Moat/Seismic Gap: To accommodate lateral movements of an isolated building, a clearance space, or “seismic gap,” must be provided around the perimeter of the base. For partially buried structures such as the containment and auxiliary buildings, the isolation system will be located below grade and the seismic gap will take the form of a moat. The width of the moat will need to exceed the maximum calculated lateral displacement under some appropriate “beyond-design-basis” seismic design criterion.

Special architectural features are associated with the seismic gap. For nuclear power plants, the seismic gap will take the form of a moat because the reactor building and auxiliary building are normally embedded several meters below grade. Construction of a moat will require retaining walls to hold the soil in place. For deeper embedment of containment/auxiliary buildings, the design and construction of the moat will need to be carefully planned. The embedment itself can be reduced to a minimum because of the reduced seismic demands provided by the base isolation system.

Another architectural consideration is the configuration of elevator pits and sumps. Typically, the elevator pits in isolated buildings are suspended below the first floor of the structure, within the space provided for the seismic isolators. Sufficient clearance will need to be provided around the elevator pits and sumps to avoid interference when the isolation system undergoes the maximum possible lateral displacement.

6. SUMMARY AND CONCLUSIONS

There are many industry/regulatory issues that need to be studied and evaluated when making the case for base isolation of US nuclear power plants. This paper addressed the following issues:

- Quality Assurance/Quality Control capabilities of isolator vendors
- Production capabilities of isolator vendors (in terms of isolator size, capacity, and production rate)
- Development of appropriate testing protocol for isolators, including testing for demonstration of long service life in a potential radiation environment with somewhat elevated service temperatures
- Development of appropriate qualification/in-production testing requirements for isolators
- The need/extent for isolator surveillance, maintenance, and in-service testing during service life
- Development of specific codes, standards, and regulatory documents for addressing design and construction of isolated nuclear facilities
- Development of suitable performance criteria, especially with inputs from equipment vendors
- Determination of the division of responsibility between the owner, engineer/constructor, and NSSS supplier, with emphasis on increased participation by NSSS suppliers
- Ability to provide suitable isolation joints for systems connected across isolated and non-isolated facilities (especially for large diameter, high-energy pipes)
- Constructability issues associated with isolation diaphragm, clearance/moat, and access space for surveillance/inspection of isolators
- Need for further isolation research, industry education and regulatory participation/acceptance

The authors believe that it is the right time to address these issues to pave the way for first deployment.

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