BASE ISOLATION FOR NUCLEAR POWER AND NUCLEAR MATERIAL FACILITIES

Report on the Status of the Practice

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ABSTRACT

This report serves to document the status of the practice for the use of base isolation systems in the design and construction of nuclear power and nuclear material facilities.

The report first describes past and current (1989) applications of base isolation in nuclear facilities. The report then provides a brief discussion of non-nuclear applications. Finally, the report summarizes the status of known base-isolation codes and standards.

INTRODUCTION

The primary purpose of this report is to bring to the attention of the Department of Energy (DOE) community the breadth of base-isolation efforts in the nuclear industry.

Seismic isolation of nuclear structures is a design approach which has been receiving increased attention in recent years. This paper reviews the background of base isolated structures, current programs which are considering seismic isolation in Europe, U.S.A., and Japan, and current code efforts related to base isolation.

To put the topic into perspective,the following list presents the past and current efforts towards base isolation of nuclear facilities.

Koeberg. Two unit PWR (2x900 MWe) plant in South Africa. Operational since 1983. Uses reinforced elastomer bearing pads with friction plates for horizontal isolation.

Cruas. Two twin unit PWRs in France. Operational since 1985. Uses reinforced elastomer bearing pads for horizontal isolation.

Superphenix 2. 1500 MWe LMFBR in France. Final design completed. Uses elastomer bearing pads and viscous dampers for horizontal isolation, and steel springs and dampers for partial vertical isolation.

Karun River. Two unit PWR (2x900 MWe) designed for Iran. Construction suspended in 1978. Uses reinforced elastomer bearings with friction plates for horizontal isolation.

Le Carnet. 1400 MWe PWR in France. Preliminary design completed; final design not initiated. This concept is relegated to future program. Uses reinforced elastomer bearings for horizontal isolation.

Laguna Verde. 1300 MWe PWR proposed by Electricite de France for Mexico. Uses reinforced elastomer bearings for horizontal isolation. Project cancelled.

LSPB. Large Scale Prototype Breeder. Conceptual study, funded by EPRI and DOE, in 1984-85.

PRISM. Power Reactor Inherently Safe Module. Liquid Metal Reactor. 465 MWe. Ongoing study, led by General Electric, Bechtel National, funded by DOE.

SAFR. Sodium Advanced Fast Reactor. 450 MWe. Recent study, base isolation considered as an alternate design option, led by Rockwell International, Bechtel National, funded by DOE. SAFR project has been stopped in 1989.

MHTGR. Modular High Temperature Gas Cooled Reactor. Cooperative design, by General Atomic, Combustion Engineering, Bechtel National, funded by DOE. 135MWe.

FBR. 1000 MWe advanced demonstration Fast Breeder Reactor, to be designed in Japan.

STPP. Seismic Technology Program Plan. A program (developed by ETEC for the DOE) to study seismic issues for LMRs. Not yet funded.

USSIRP. United States Seismic Isolation Research Program. A program (sponsored by the National Science Foundation) to lead to implementation of seismic isolation as a standard economic strategy. Not yet funded.

EPRI/CRIEPI/CEGB. A joint program between EPRI (USA), CRIEPI (Japan) and CEGB (England) to study seismic isolation systems for LMRs.

CRIEPI. A seven year research program by CRIEPI in seismic isolation, begun in 1987, Japan.

Base isolation topics have become prevalent in nuclear plant oriented conferences over recent years. For example, the 1983 SMIRT had one session dedicated to seismic isolation, with a special volume of the Journal of Nuclear Engineering and Design [Vol. 84, No. 3, 1985] published which presented a set of invitational papers on themes developed at this SMIRT session. Each subsequent SMIRT has included further base isolation papers, and the 1989 SMIRT devoted four sessions in the main conference, and four additional sessions in a special Post-SMIRT Seminar to this topic.

The annual Pressure Vessel and Piping conferences organized by ASME have also included symposia on seismic isolation. The first and second Symposia on Seismic, Shock, and Vibration Isolation were held in 1987 and 1988. Sixteen and fourteen papers were presented at these two conferences, respectively [1,2]. A third symposium held in 1989 had twenty four papers presented on this topic[3].

To this date, no licensee in the United States has approached the Nuclear Regulatory Commission with a request to operate a complete nuclear plant built on a seismic isolation system. The reasons that this is so are several, and among the primary reasons are the following:

- The base isolation technology has blossomed only in the late 1970s and 1980s - and since 1978 no new reactor orders have been placed in the United States
- There are no NRC-approved guidelines, or codes, that define the design basis needs for nuclear plants on base isolation systems. Perceived difficulties and delays in licensing may deter application
- The cost savings (or dis-savings) of a base-isolated nuclear plant have not yet been quantified or proven in practice for different sites; and such cost savings (or dis-savings) are not widely recognized by design practitioners.

As of 1989, the need for new nuclear facilities presents the opportunity to examine the seismic isolation option. The potential for new nuclear facilities is evident for the following reasons:

- The Department of Energy (DOE) has determined the need for a new tritium producing reactor
- The DOE has an ongoing program to investigate new types of reactors, both for possible military or energy production purposes, which are considered "safer" than those presently in operation in the United States
- The move toward standardization and a one-stop licensing process improves the potential for seismic isolation as a means to make standardization possible

• Utility owners in the United States are seeing their overcapacity rapidly eroding, due to the continued expansion of the economy; and losing existing capacity due to retirement of older facilities, or excessive polluting facilities. Thus, they may in the near future begin to order new plants.

For these reasons, an early review, evaluation and development of seismic base isolation in the context of the US nuclear environment is important.

This report describes the background of base isolation for nuclear plants; describes many of the nuclear facility base isolation designs either already implemented or in current design; presents a brief status of non-nuclear applications; and discusses current codes and guidelines.

Topics such as detailed design issues; experience of actual base-isolated structures, or areas needed for further development are beyond the scope of this status report. These important topics have been, and will continue to be described in the technical literature, probably at an ever-increasing pace.

NUCLEAR PLANT BACKGROUND

To reduce capital costs so that future nuclear plants are competitive with those using alternate sources of energy, large portions of the plant should be standardized. Furthermore, to gain public acceptance, these plants must be reliable and should have several passive inherent features to provide public safety and plant investment protection. Seismic design can play a major role in achieving a standardized design which could accommodate varying seismic conditions. One approach to standardization would be to design a plant using traditional methods for a safe shutdown earthquake (SSE) which envelopes the responses of 90% of existing U.S. nuclear sites. This would lead to high seismic loads especially in components and equipment and would still exclude California sites and limit exporting potential of these plants to high seismic countries. Liquid Metal Reactor (LMR) designs which consist of thin walled vessels designed to accommodate large thermal transients under low operating pressures are more sensitive to seismic loads and thus would be particularly penalized by this approach.

An alternative would be to seismically isolate the plant. Seismic isolation is a recent development that is gaining rapid worldwide acceptance in the commercial field[4] and is being implemented in advanced nuclear designs of the future [5]. This approach decouples the structure from the components of ground motion which are predominantly responsible for structural damage, resulting in significant reductions in seismic loads. Thus the design and qualification of equipment and piping becomes a simpler task than today. Since the response of isolated structures is highly predictable, the risk of accidents due to uncertainties in the input motions is reduced, safety margin is increased, and plant investment protection is enhanced. If seismic design criteria are upgraded, for example due to the discovery of new geotectonic conditions, the standard plant design would probably not have to be altered and only the isolation system would need to be updated.

Due to the high cost of development of LMR designs and limited available resources, international cooperation could be highly desirable, particularly for the nuclear steam supply system (NSSS) components. Seismic isolation would facilitate the development and application of an international standard design of the NSSS and would allow the decoupling of the NSSS design development, which is global in nature, from the balance of plant (BOP) design and licensing which is regional in nature. BOP designs can be developed by each country in accordance with its own local requirements without impacting the standard NSSS design. This would enhance the opportunities of international collaboration in the development of the NSSS for LMR plants.

Several advancements in recent years are responsible, for making seismic isolation a practical alternative. These include the development of highly reliable elastomeric compounds used in seismic bearings which are capable of supporting large vertical loads and can accommodate large horizontal deformations during the earthquake without becoming unstable. Additionally, the development of high damping elastomers and other mechanical energy dissipaters to control resulting displacements in the isolators, has provided the opportunity to keep the response to manageable levels. The development of verified computer programs, the compilation of reliable test results of individual seismic isolators under extreme loads, shake table tests for evaluating system response, and validation of computer programs all add to our confidence in being able to predict the response.

CURRENT PROGRAMS - FRANCE

France has succeeded in establishing an economically competitive nuclear program due to the successful implementation of a standardized 900 MWe PWR plant. This design is suitable for the majority of sites in France where seismic accelerations are less than 0.2 g. When a plant is to be located at a site with higher seismicity, seismic isolation is specified to limit seismic loads in the plant to the levels that the standard design can accommodate. The system was developed by Spie-Batignolles and Electricite de France[6]. The reactor, fuel, electrical, maintenance, and auxiliary buildings are placed on a common upper mat which is in turn supported on pedestals cast integrally with the lower mat with the isolators placed in between. The type of isolator used depends on the site acceleration level. For sites with moderate seismicity, relatively thin steel laminated elastomeric pads are used.

CRUAS

The operational two twin-unit Cruas-Meysse plants (total 4x900 MWe) are located in the Rhone Valley of France. The site SSE acceleration is 0.2 g. The plants are supported on 1800 pads, each measuring 50x50x6.5 cm [7]. The pads are similar to standard neoprene bridge bearing pads. They have three layers of elastomer, each 13.5 mm thick reinforced with 3 mm-thick steel plates and 10 mm thick top and bottom plates. An isolation system is used for this site since there is a probability of shallow earthquakes of low magnitude (Richter 4 to 4.5) occurring close to the site producing higher accelerations and high frequency motion. The fixed base frequency of the reactor building is roughly 4.5 Hz and corresponds to the peak frequency of the anticipated spectrum. With the pads, the frequency is reduced to 1 Hz which significantly reduces the forces on the structure and internal equipment. The maximum displacement capacity of the pads is only 5 cm, but due to the high frequency input, the anticipated displacement is only 2.6 cm.

Including the lower raft, retaining wall, pedestals and bearings, the cost of the isolation system at Cruas is about 2% to 3% of the total civil works cost.

KOEBERG

A nuclear power plant in South Africa has been built on an isolation system by the French construction company Framatome[8,9]. The Koeberg plant is based upon the French 2x900 MWe design. In South Africa, it is located at a site with higher seismicity than that at Cruas, with a SSE level of 0.3g.

For this higher seismicity, the base isolation system includes both elastomeric bearings and friction plates. The friction plates are placed between the top of the pads and the upper mat. The lower plate is made of a lead-bronze alloy and the upper plate which is embedded in the upper mat is stainless steel. The plate combination provides a friction coefficient of 0.2. When the ground accelerations exceed the friction coefficient, slip occurs, thus limiting the level of shear strains in the pads and the forces in the building to the same level as that for moderate sites. A total of 2000 pads 70x70x10 cm were used.

The construction costs for this system were justified in that it allowed a standardized plant to be built at a site with no (or little) additional costs for redesign, strengthening and requalification of components.

KARUN RIVER, IRAN

The design of the Karun River nuclear power plant incorporates the standard 2x900 MWe reactor units. The plant layout is very similar to that at Koeberg. Construction permit for the plant was granted in 1978. Construction activities at this site were suspended in late 1978 after completion of the lower raft. The isolation bearings for this plant had been fabricated and shipped to the site.

The seismic design criterion at the Karun River site was defined by USNRC R.G. 1.60 response spectra anchored to a horizontal peak ground acceleration of 0.3g. The bearings are about 65 cm square in plan and comprise six layers of elastomer. The interior layers are 16 mm thick and the exterior layers are 8 mm thick. The bearings are reinforced by 5 mm thick steel shims. The total height of a bearing is about 13 cm. Similar to the Koeberg design the isolation system at Karun River includes a friction interface to help dissipate the seismic energy and limit the response of the isolated nuclear island.

SUPERPHENIX-2

Seismic isolation has been incorporated in the design of a large 1500 MWe liquid metal fast breeder reactor (LMFBR), the Superphenix 2. The entire nuclear island is isolated in the horizontal direction using elastomeric pads and viscous dampers and additionally, the reactor cavity is isolated in the vertical direction using steel springs and viscous dampers. Special guides are implemented between the reactor cavity and the reactor building to minimize rocking of the reactor.

The final design of Superphenix 2 has been completed. The construction of this plant awaits feedback and operating experience from Superphenix 1 and an improvement in energy demand projections.

OTHER FRENCH PWR DESIGNS

Designs were also developed for a single 1300 MWe PWR at Laguna Verde Mexico, and a two unit 1400 MWe PWR at Le Carnet in western France. Two types of isolation systems were considered: elastomeric pads with sliders, and ordinary pads with German GERB type viscous dampers in parallel to limit horizontal displacements. These designs were not implemented.

OTHER FRENCH NUCLEAR FACILITY DESIGNS

Other isolated nuclear structures include a three story reinforced concrete radioactive waste processing building supported on GAPEC type laminated elastomeric bearings[10] and three spent fuel storage pools at the La Hague reprocessing plant[11].

OTHER EUROPEAN DESIGNS

The current status of seismic isolation of LMFBRs in Europe was discussed in a Specialists' meeting on Fast Breeder Reactors. The results of this meeting are summarized by Martelli[12]. The main conclusion was that for LMFBRs, seismic isolation offers sufficient advantages to warrant further development to resolve some of the outstanding technical problems.

In England, British Nuclear Fuels have designed a nuclear fuel reprocessing facility as a base isolated structure.

UNITED STATES

Studies have been performed to review available isolation devices and to examine their applicability to U.S. nuclear design[13,14]. Interest in adapting seismic isolation to LMFBRs has gained interest: under the sponsorship of DOE and Electric Power Research Institute (EPRI), studies were performed to apply isolation to the Large Scale Prototype Breeder (LSPB) reactor plant. Several types of isolation systems[15,16,17] were reviewed. These studies concluded that there were significant advantages to isolate LSPB.

Since completion of the LSPB studies, DOE has been supporting the development of three compact advanced reactor concepts, the first two are LMRs: the Power Reactor Inherently Safe Module (PRISM); the Sodium Advanced Fact Reactor (SAFR); and a Modular High Temperature Gas Cooled Reactor (MHTGR). The PRISM design has been selected as the U.S. reference Advanced Liquid Metal Reactor. The PRISM LMR concept incorporates seismic isolation in the reference design to enhance plant safety margins, to support plant standardization, and to potentially reduce plant costs. The SAFR LMR concept incorporated seismic isolation as an alternate design: recently (1989), the SAFR project was stopped. For MHTGR seismic isolation is being studied for adapting the non-isolated reference design, developed for moderate seismic zones, to high seismic sites. Both the PRISM and MHTGR projects continue to be funded as of late 1989.

PRISM

PRISM is a compact standardized LMR reactor installed in blocks consisting of three reactors per 465 MWe power block[18]. It incorporates a horizontal isolation system to isolate the reactor module with its key safety functions of reactor shutdown, shutdown heat removal, and containment systems. The small diameter of the PRISM vessel provides sufficient intrinsic resistance in the vertical direction to minimize amplifications in vertical ground motions and makes vertical isolation unnecessary. The total weight of these structures is approximately 4500 tons. The isolation system selected consists of 20 high damping steel laminated elastomeric bearings. The bearings have a diameter of 132 cm and a total height of 58.7 cm and consist of thirty layers of rubber 1.27 cm thick and 29 steel plates 0.32 cm thick. The bearing dimensions were selected to give a horizontal frequency of 0.75 Hz and a vertical frequency over 20 Hz. The entire isolated structure is housed in an underground silo.

The design SSE for PRISM is a maximum horizontal and vertical acceleration of 0.3 g anchored to a design earthquake that envelopes the NRC Regulatory Guide 1.60 spectra. Options for siting in higher seismic zones have been retained. Analytical results show that horizontal accelerations are substantially reduced in all the reactor components with isolation[19]. The peak spectral acceleration at the core support plate for 2 percent damping was reduced from 16.5 g to 0.25 g. Furthermore, horizontal spectral peaks above 2 Hz are eliminated.

A series of quasi-static tests were performed at the University of California Earthquake Engineering Center (EERC) in Richmond on four half-scale bearings. Each bearing had a diameter of 66 cm and consisted of thirty alternating layers of rubber 0.63 cm thick and 29 steel plates. The bearings were first tested to design conditions expected during an SSE. The tests verified that the bearings are capable of undergoing several cycles of varying shear strain without appreciable change to their stiffness or damping. Furthermore, the bearings have 10% damping or more for all applicable strains[20]. The bearings were then subjected to extreme loads resulting in a maximum horizontal displacement of 36.6 cm which corresponds to 200% shear strain in the rubber and which is three times larger than the displacement computed for the SSE. The high performance margins of the bearings were thus demonstrated by the fact that the bearings were capable of sustaining displacements triple the SSE-displacements without failure or damage[21]. One of the bearings was subjected to a vertical load of 1800 tons with no failure.

Similar half-scale bearings with bolted type connection instead of dowelled connection have been tested to compare the failure mechanism of the two systems. Tests in Japan have shown that bolted bearings can accommodate larger horizontal displacements than dowelled ones. The PRISM design,which currently uses dowelled connections will be reassessed depending on the outcome of these tests. The test series are repeated for quarter-scale and full-scale bearings to determine the effects of scaling on bearing performance characteristics and failure modes.

The Energy Technology Engineering Center (ETEC) is in the process of assembling a large bearing test machine under DOE funding. The fixture will be ready for testing PRISM half-scale bearings similar to the ones tested at EERC. The main objective of these tests is to compare and quantify the effects of dynamic loading on bearing response. The machine capacity was selected based on testing full-scale PRISM bearings dynamically. It will be capable of testing a single bearing up to 152 cm in diameter and 91 cm high under a maximum vertical load of 750 tons and a maximum horizontal load of 150 tons with a horizontal stroke of $\pm$38 cm up to a frequency of 0.75 Hz and is also capable of applying a maximum static horizontal displacement of 63 cm.

Other programs planned to qualify the PRISM seismic isolation design include: shake table performance tests modelling a large weight, which represents PRISM's mass distribution, on a set of bearings to evaluate system performance during real earthquakes and to evaluate the effects of input with strong long period energy. large scale shake table test, seismic hazard assessment, and the development of design guidelines[22].

Argonne National Laboratory (ANL)[23] is working with Shimizu of Japan on a joint U.S./Japanese program for testing PRISM type bearings in a unique facility built by Shimizu at Tohoku University in Sendai, Japan. The facility consists of two full-size three story buildings built side by side identical in every way except one structure is seismically isolated and the other is not[24]. ANL has furnished the elastomeric bearings to test the bearing performance under actual earthquakes and during static and dynamic forced vibration tests. Comprehensive analysis of the building response is also planned. The resulting information will provide correlations between laboratory test data obtained at EERC and ETEC and field data. ANL's effort is funded by the National Science Foundation; the program is expected to last two years.

SAFR

(The DOE is no longer funding further work on the SAFR design. The following description describes recently completed work).

The SAFR plant concept employs a 450 MWe pool type LMR as its basic module. The reactor assembly module is a standardized shop-fabricated unit that can be shipped to the plant site by barge for installation[25]. The SAFR plant ensures both public safety and investment protection by means of a variety of passive and localized features. It incorporates inherent capability for reactor shutdown and adequate core and spent fuel cooling under all circumstances. The seismic design basis is a SSE level of 0.3 g. To enhance seismic margins, and to permit siting in regions of high seismicity, studies were performed to investigate the feasibility of isolating the SAFR reactor building.

Three isolation concepts were considered: horizontal isolation of the entire nuclear island; a hybrid system similar to the one proposed for Superphenix 2 in which the building is isolated in the horizontal direction and the reactor cavity is isolated in the vertical direction; and full three dimensional isolation whereby the building is simultaneously isolated in both horizontal and vertical directions. After reviewing the merits of each concept the third concept was incorporated in an alternate to the reference design. This uses a new type of isolation system which consists of low shape factor steel laminated elastomeric bearings with high damping which provide flexibility in both the horizontal and vertical directions. The total isolated weight is 39,000 tons. Approximately 100 bearings with a diameter of 107 cm and a total height of 42.6 cm are utilized. The horizontal frequency is 0.5 Hz and the vertical frequency is around 3 Hz. In general, a large amount of rocking will result in buildings supported on such bearings. However, the SAFR building has a sufficiently low center of gravity and a wide base to limit rocking to acceptable levels.

This type of isolation system has not been previously tested. Dynamic tests of prototype quarter-scale bearings have been performed at EERC to examine the feasibility of using the proposed bearings for three-dimensional isolation of nuclear buildings and to verify the applicability of existing design formulas to low shape factor bearings. Two types of bearing connections were tested: a dowel type, and a rigidly bolted type. Stability and failure limits of the two designs are being assessed. Results of these tests should be available in late 1989.

MHTGR

The MHTGR advanced reactor concept is being developed under a cooperative program involving DOE, the utilities, and the nuclear industry. The reactor capacity which is 135 MWe and the configuration selected provides a higher margin of safety and investment protection than current generation reactors[26]. The standard MHTGR reactor and steam generator are enclosed in a concrete silo which is fully embedded to minimize seismic loads. The standard design which does not include seismic isolation was developed to envelope the seismic conditions at 85 percent of U.S. nuclear sites using a maximum SSE of 0.3 g. An initial investigation into the feasibility of seismically isolating the MHTGR to extend available sites into areas of higher seismicity was recently completed by Bechtel National Inc. For high seismic sites, such as along the California coast, it is anticipated that the plant would be designed for a SSE of approximately 0.7 g. A concept for horizontally isolating the reactor vessel and steam generator while minimizing the impact on the reference plant layout was developed. The isolated structure is supported on 42 high damping elastomeric bearings. The design was based on a horizontal isolation frequency of 0.60 Hz. Unresolved issues which need further investigation include radiation resistance and shielding of the bearings, inspectability and replaceability of the bearings, and design of systems such as the main steam and feedwater pipes passive cooling ducts to accommodate the large relative movements between the isolated structure and the fixed silo. The feasibility of three dimensional isolation using either elastomeric bearings as proposed in SAFR with a vertical frequency between 4 and 5 Hz, or steel springs and viscous dampers will also be studied.

SEISMIC TECHNOLOGY PROGRAM PLAN

The Seismic Technology Program Plan (STPP) has been coordinated by ETEC[27] for the DOE to minimize the impact of seismic design on advanced LMR development and to avoid costly seismic design problems associated with LWR experience. Specific goals of the STPP are to identify and to prioritize research and development needs, and to provide the basis for a LMR seismic design guide. Five research and development needs are identified, with seismic isolation verification given the highest priority. For seismic isolation, a six year program costing $9.0 million is defined. The objectives of this program would be to test several types of isolation systems, to develop and verify the necessary tools to analyze isolated systems, to develop appropriate seismic inputs including long period motion effects and accounting for beyond design basis events, collecting and analyzing performance data of existing isolated structures and evaluating the integrated effects of earthquake characteristics on the seismic risk to isolated plants. The results of this program will produce a validated seismic design and analysis technology.

Depending upon whether additional improvements are made to other areas of seismic technology, a base isolated plant is projected to save , versus a non-base-isolated plant, in a high seismic zone, about 5% to 10% of the total plant cost.

UNITED STATES SEISMIC ISOLATION RESEARCH PROGRAM

The USSIRP is a coordinated National Science Foundation research program that will lead to the implementation of seismic isolation in the United States as a standard economic strategy, compatible with existing design codes, in five years time. It is intended to apply to non-nuclear construction, but will likely produce results useful to the nuclear industry. The program is not yet funded.

In principal, the program will be led by a technical coordinator who will be assisted by four advisory panels, as follows:

- Executive Panel. Includes researchers within the program, one from each research area.
- Consulting Engineers Panel. Includes practicing structural engineers actively engaged in the design of base isolated structures.

• Users Group Panel. Includes experts from companies and organizations that are identified as most probable users of the technology.

• Materials Panel. Includes representatives of base isolation hardware suppliers.

The USSIRP is organized to have five research groups that work as a coordinated program to produce the required products. The groups are: Ground Motion; Modeling and Dynamic Response; Design Criteria; Materials; Economics.

EPRI/CRIEPI/CEGB SEISMIC ISOLATION PROGRAM

EPRI and CRIEPI have been collaborating in a joint program to evaluate the technical feasibility of selected seismic isolation systems and their applicability in the design of LMRs[28]. Available seismic isolation devices have been evaluated and candidate systems have been selected. Reduced and full scale tests of these isolators and shake table tests are planned. These will provide confirmation of final design input for an isolated plant design.

The first phase of this program consisted of testing half scale elastomeric bearings with lead plugs[29] to confirm performance characteristics to investigate failure modes and to verify restoring capabilities. The bearings tested measured 25.4x25.4x6.5 cm and were manufactured in the U.S. according to specifications provided by Burns and Roe, Inc., the contractor assisting EPRI in the program. U.K.'s Central Electric Generating Board (CEGB) has joined the program in its second phase. A second isolation system consisting of laminated elastomeric pads 15x15x7 cm and GERB type viscous dampers provided by CEGB are being tested by CRIEPI. After completion of these tests, full scale elements will be tested.

NUCLEAR PLANT COSTS FOR SEISMIC DESIGN AND UPGRADE

One driving force to consider base isolation is the excessive costs and delays associated with the seismic design of nuclear plant facilities. These costs and delays have been attributed to overly conservative seismic design requirements and procedures that have been adopted in a rapidly evolving and increasingly stringent regulatory environment. Resulting plant cost increases in excess of $300 million have been documented[30], and approximately 40% of current License Event Reports filed with the NRC are related to seismic design issues[31].

As demonstrated by the designs for Koeberg and Cruas, one can save the existing design basis for a plant, should a new source of seismicity be discovered after the plant has been designed. The San Onofre Unit 1 plant is an example of the costs associated with new-found "seismicity"at an operating nuclear plant. This plant was originally designed to a 0.50g motion, using the design rules of the late 1960s. Later, Units 2 and 3 were built alongside Unit 1, and the new geotechnical investigations led to the increased seismic design basis on Unit 1 to 0.67g. Approximately $180 million was spent on redesign and construction to bring Unit 1 up to 0.67g; this amount excludes any lost generating capacity costs of a forced 23 month outage while new hardware was designed and installed. If this plant had used a seismic isolation system, then the increase in seismicity could have been adjusted for by altering the structural characteristics of the isolation system.

Other recent examples of high seismic design costs include the Comanche Peak station - whose SSE motion is 0.12 g, yet has had to undergo a multi-year seismic re-verification process costing in the many hundreds of millions of dollars, to satisfy the plant's design basis. More examples are the seven Units owned by TVA (Browns Ferry 1,2 and 3, Watts Bar 1 and 2 and Sequoyah 1 and 2), each of which has recently undergone seismic upgrade programs to satisfy design basis issues. Multi-million dollar seismic upgrade programs have occurred at almost every operating plant in the United States. For all these existing plants, seismic upgrades have proved to be expensive, chiefly due to the large amounts of commodities (piping, raceways, anchorages, etc.) within these facilities which need to be checked under new or altered seismic loads. Little of this would be needed in a base-isolated plant, as these commodities see very small seismic loads in the first place, and any increase in site seismicity, or validation needs of design bases, would use up little of the large margin inherent in these commodities.

JAPAN

Interest in seismic isolation in Japan has increased significantly in recent years. Research and development in isolation is being carried out by several of the major construction companies which have to date implemented isolation in over 30 buildings. These companies have decided that seismic isolation is superior to conventional seismic design and can give a company a competitive edge in the construction industry. Several universities and government agencies are also participating in different research programs.

One of the reasons for the rapid development of this technology is the availability of state of the art bearing test machines at several of the companies involved in seismic isolation development. Most notable among them is Kajima's machine which was brought to operation in 1988. This unique machine is capable of applying independent horizontal loads along two perpendicular axes in real time while simultaneously maintaining a vertical load. The availability of several large shake tables has allowed the promotion of seismic isolation to the public by comparing the performance of non-isolated structural models with isolated models. The largest shake table in the world is at Tadotsu and is 15x15 m in plan dimensions and has a maximum loading capacity of 1000 tons. A maximum horizontal acceleration of 1.84 g and a maximum vertical acceleration of 0.92 g can be applied. The table has been used for testing several large scale nuclear components for LWRs. Scale factors ranged from 1 to 3.7 with model weights from 290 to 750 tons.

Seismic isolation is also gaining support in the Japanese nuclear industry. This is especially true among companies and utilities participating in the development of the advanced demonstration FBR plant (DFBR) whose construction is expected to start in the mid to late 1990s. At present, an important factor inhibiting the commercialization of FBRs is the construction cost. The cost of Monju, a demonstration plant with a capacity of 280 MWe, is nearly twice that of commercial light water plants of the 1000 MWe class[32]. Seismic isolation is expected to reduce significantly the cost of seismic design in FBRs and to facilitate standardized FBR designs for a wide range of siting conditions.

Research and development has been required to develop isolation systems with the required reliability for nuclear applications. Performance experience of isolated structures must be gained in less critical structures as a precondition for accepting seismic isolation for nuclear plants. Thus, research in this field is receiving large support from the government and electric companies. The Central Research Institute of Electric Power Industry (CRIEPI) is managing a seven year research program in seismic isolation, which started in 1987. The objectives of this program are: establishment of a seismic isolation design for the LMFBR; selection of appropriate seismic isolation devices; performance of large scale element tests of selected devices; performance of large scale system tests on the Tadotsu shake table; construction and observation of the response of a large scale isolated nuclear building model; observation and cataloging of the response of all isolated buildings in Japan during earthquakes; identification of a set of design earthquakes with long period components; and the development of design guidelines for isolated nuclear systems.

Different concepts of isolation are being considered. This includes total base isolation of the nuclear island building (NIB) or isolation of the reactor cavity in the horizontal direction (2-D) or in the vertical plus horizontal directions (3-D), or hybrid isolation where the NIB is isolated in the horizontal direction and the reactor cavity in the vertical direction. It is recognized, however, that vertical isolation is more difficult and since all the buildings isolated in Japan use horizontal isolation only, it would be more difficult to collect performance data on vertically isolated buildings in the near future. Thus, it is expected that if seismic isolation is selected for the first DFBR, only horizontal isolation will be adapted, while keeping vertical isolation an option for future applications. Several types of devices are being considered including steel laminated high damping elastomeric bearings, elastomeric bearings with various energy absorbers including lead plugs, steel dampers, viscous dampers and friction dampers and coil springs with viscous dampers.

The lead reactor manufacturer and construction companies participating in this program are Hitachi and Kajima, respectively. In a joint study it was shown that the design of FBRs could be greatly simplified if seismic isolation is used[33]. For example, the total reactor building weight could be reduced by more than fifty percent. The two other major reactor manufacturers, Toshiba and Mitsubishi Heavy Industries and the remaining top five construction companies are also participants. Another program[34] investigated the effect of damping type on the performance of equipment in isolated structures. Four types: friction, lead, oil, and viscous were tested. It was concluded that viscous damper gave the best attenuation of accelerations in equipment. The study recommended that the choice of damping should be selected based on the application. Shake table tests performed at EERC have also demonstrated that accelerations in equipment in isolated structures are minimized when high damping elastomeric bearings with no add-on damping elements are used. However, when other elements are added to provide additional damping, they inevitably cause high frequency response and increased accelerations in equipment[35,36]. The advantages of using high damping rubber bearings in nuclear applications and a summary of these test results have been studied[37]. The feasibility of using lead filled elastomeric bearings for horizontal isolation was investigated experimentally[38]. Feasibility of 3-D isolation using steel coil springs and viscous dampers was studied experimentally and analytically[39]. A hybrid system in which the building is isolated horizontally using elastomeric bearings and the reactor floor is isolated vertically on steel springs is under investigation[40].

NON-NUCLEAR APPLICATIONS

This report has emphasized the current status of base isolation for nuclear facilities. As of 1989, there are more than 100 applications of base isolation in non-nuclear facilities, mostly for bridges and low rise structures. Most applications are in New Zealand (>40); there are several in Japan (>30), and United States (>15); Canada, China, England, France, Greece, Iceland, Iran, Italy, Mexico, Romania, USSR, and Yugoslavia all have at least one application. Almost all applications have been built in the 1980s. The 1990s may very well be a decade where base isolation in the non-nuclear world "comes into its own", with many hundreds of applications.

As of the date of writing this paper, no existing base isolated structure has undergone a truly "major" earthquake. Several buildings have performed well through earthquake motions on the order of 0.01g to 0.05g, and one (the Okumura building in Tsukuba, Japan) has performed well in a 0.20g earthquake. The Te Teko bridge in New Zealand has experienced an approximately 0.3g ground motion. Post-earthquake studies have shown that these structures have performed as predicted in design.

Perhaps the most promising areas for non-nuclear application is in the area of isolating facilities whose functionality following a very large earthquake is important to society. Candidate structures are power generating facilities; hospitals; etc. Similarly, facilities which house very expensive, or sensitive, equipment, like computers, are also candidates.

Some key aspects as to whether to or not to base-isolate such structures are whether the facilities need to be operable after the earthquake; or whether the facilities cannot afford to incur unacceptable high damages/outages post-earthquake. In this respect, the important "cost " issue, as seen by the owner of such a facility, will include both initial construction as well as lifetime operations costs.

CODE EFFORTS

This section of the report summarizes the status of various groups throughout the world to develop codes (or guides) for design of base-isolated structures. The technical aspects of the design codes or guidelines are not provided herein, partially since they are lengthy, and partially since some are not yet published.

UNITED STATES

The Seismology Committee of the Structural Engineers Association of California (SEAOC) has recently completed the development of seismic regulations for the design of base isolated structures[41]. These regulations are an update of the seismic requirements developed by the Northern Section of SEAOC and published in 1986[42]. The SEAOC regulations have been submitted to the International Conference of Building Officials (ICBO) for consideration as Division III of Chapter 23 (General Design Requirements) of the Uniform Building Code[43]. After review and adoption by ICBO, these regulations will be published as an appendix to supplement existing seismic design requirements for conventional fixed-base buildings and are intended for use with non-nuclear base isolation applications.

EUROPEAN COMMUNITY

The design of structures in member countries of the European Community will be governed by Eurocode No. 8, which will become effective in 1992. Part 5 of this code is concerned with foundations. A proposed section, Annex 5A, addresses design of base isolated structures. This annex is preliminary and will undoubtedly be influenced by ongoing code work in member countries, such as France and Italy.

FRANCE

A French base-isolation design code is currently being developed. When complete, this code will be adapted as a chapter in the French earthquake code, "Regles Parasismiques P.S. 1986." The responsible agency for the French seismic code is the Association Francaise Parasismiques, located in Saint Remy. An initial draft of the base isolation code is expected by the end of 1989. The code is intended for the regulation of non-nuclear structures, but will also establish minimum requirements for nuclear applications.

ITALY

Since 1988, the Italian National Commission for Atomic and Alternative Energy Sources (ENEA) in cooperation with the Italian institute, ISMES, has been developing design guidelines for seismic isolation of nuclear reactors. A preliminary draft has already been prepared by ENEA and an updated version should be available in late 1989.

JAPAN

In Japan, two groups are developing guidelines for the use in non-nuclear applications. First, the Architects Institute of Japan (AIJ) is developing design guidelines for use by the building designer. A first draft of this document is expected by late 1989. Separately, the Building Center of Japan is developing guidelines for use by oversight committees in the review of isolated buildings. The Ministry of Construction of Japan requires all base-isolated buildings to have a special construction permit that involves extensive review by the Building Center. A draft of this document is also expected in late 1989.

With respect to nuclear construction applications, the CRIEPI is pursuing an extensive base isolation research program for isolated nuclear structures including the development of design guidelines. The research program is long term and final design guidelines are not expected until 1992.

NEW ZEALAND

In New Zealand, where the application of seismic isolation to bridges is quite common, the Ministry on Construction has developed internal regulations for the design of isolated bridges. Isolated buildings have been regulated on a case-by-case basis.

CHINA

In 1987 the Seismic Isolation Committee was established under the Architectural and Structural Society of China, and activities in code development have started. Each implementation of base isolation in China to date has happened individually, with advance approval by authorities.

CONCLUSIONS

Seismic isolation is a significant recent development in earthquake engineering that is gaining rapid worldwide acceptance in the commercial field and is being implemented in advanced nuclear designs of the future. Since the seismic response of isolated nuclear structures is of a predictably lower amplitude, the risk of accidents due to uncertainties in the input motions can be reduced, public safety margins can be increased, plant investment protection can be enhanced, and standard plant design can be achievable. Progress in codes and standards should soon make the base isolation option a viable alternative for the design of nuclear facilities in the United States in the next few years.

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