IAEA-TECDOC-1905

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Seismic Isolation Systems for Nuclear Installations

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SEISMIC ISOLATION SYSTEMS FOR NUCLEAR INSTALLATIONS

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IAEA-TECDOC-1905

SEISMIC ISOLATION SYSTEMS FOR NUCLEAR INSTALLATIONS

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2020

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Printed by the IAEA in Austria
May 2020

IAEA Library Cataloguing in Publication Data

Names: International Atomic Energy Agency.
Title: Seismic isolation systems for nuclear installations / International Atomic Energy Agency.
Description: Vienna : International Atomic Energy Agency, 2020. | Series: IAEA TECDOC series, ISSN 1011–4289 ; no. 1905 | Includes bibliographical references.
Identifiers: IAEAL 20-01308 | ISBN 978–92–0–106520–9 (paperback : alk. paper) |
ISBN 978–92–0–106720–3 (pdf)
Subjects: LCSH: Nuclear facilities. | Seismic waves — Damping. | Earthquake resistant design.

FOREWORD

One of the statutory functions of the IAEA is to establish or adopt standards of safety for the protection of health, life and property in the development and application of nuclear energy for peaceful purposes. The IAEA is also required to provide for the application of these standards to its own operations as well as to assisted operations and, at the request of the parties, to operations under any bilateral or multilateral arrangement, or, at the request of a State, to any of that State's activities in the field of nuclear energy.

This publication provides information on protection of nuclear installations against seismic events. It presents international practices and applications of seismically isolated systems that improve the seismic performance of structures, systems and components.

The methodology used to design seismically isolated systems has been tested and demonstrated to be effective in numerous non-nuclear seismically isolated buildings, bridges and other structures around the world, and several countries, including France and South Africa, have successfully constructed and operated seismically isolated nuclear installations. Moreover, in the light of the 2007 Niigataken Chuetsu-oki earthquake's effects on the Kashiwazaki-Kariwa nuclear power plant, Japanese utility companies decided to build new base-isolated emergency buildings for each site. The behaviour and performance of these structures during the Great East Japan earthquake in 2011 confirmed the reliability of the design of these seismically isolated systems.

This publication supports the revision of IAEA Safety Standard Series No. NS-G-1.6, Seismic Design and Qualification for Nuclear Power Plants. The IAEA is grateful to all those in the international scientific community who contributed to the drafting and review of this publication. The IAEA wishes to thank P. Sollogoub for contributing to the drafting of the publication and A. Whittaker for comments and review. The IAEA officers responsible for this publication were O. Coman and N. Stoeva of the Division of Nuclear Installation Safety.

CONTENT

1. INTRODUCTION

1.1.BACKGROUND

Seismic Isolation (SI) use has been growing over the last 20 years (Japan, USA, France, Italy). The most common applications are on conventional (non-nuclear) structures, such as buildings, bridges, offshore oil and gas platforms, high hazard storage tanks, industrial facilities, etc. Their design is based on developed codes and standards with controlled manufacturing and on-site construction procedures. These developments constitute the design and analysis techniques which are mature and reliable.

To date, the number of applications on nuclear installations is relatively small but growing. Earthquake engineers around the world are considering base isolation systems to be applicable for nuclear installations as defined by the IAEA.

In principle, seismic isolation can be applied to new and existing nuclear power stations, processing facilities, and other nuclear facilities. Although it is easier to apply it to new structures, retrofit of complete structures and buildings with base isolation systems has been performed in the past. In existing facilities, seismic upgrade based on seismic isolation of a component, a system, or a sub-structure is also possible.

This publication relates to a number of IAEA Safety Standards, namely: SF-1 [1], SSR-1 [2], SSR-2/1 [3], SSR-2/2 [4], SSR-3 [5], SSR-4 [6], SSG-9 [7], NS-G-1.6 [8], NS-G-2.13 [9]. It complements these IAEA Safety Standards as a technical publication on the behaviour of seismically isolated SSCs in nuclear installations. Thus, this publication contributes to the implementation of IAEA Safety Standards by providing detailed technical basis in relation to seismic analysis, seismic design, and seismic safety evaluation; particularly, for the revision of Safety Guide NS-G-1.6 [8], Seismic Design and Qualification for Nuclear Power Plants.

The following paragraphs provide an overview of seismic isolation

a. The basic concept of seismic isolation is to filter out the medium and high frequency part of the seismic excitation applied to a building, a group of buildings, a component, a system, or a sub-structure.
b. This is achieved by adding flexible or sliding elements (isolators) between the structure to isolate and its support. The isolators shift the effective fundamental frequency of the isolated structure to low values, typically below 1 Hz, where the energy content of the seismic excitation is lower. It induces a reduction of the inertial forces and accelerations transferred to the structure and to the components and systems it may host.
c. As a consequence of lowering its effective fundamental frequency, the displacement response of the isolated structure relative to its support is increased. To limit this increase, damping devices are frequently integrated in the seismic isolation system.
d. Most of the existing isolation systems are effective in the horizontal directions only. They provide flexibility in the horizontal direction while being relatively rigid in the vertical direction. The vertical rigidity is due to the fact that they bear the weight of the isolated structure, and that they do so without inducing large deflections or rotations of the isolated structure. The two main categories of isolators performing the above-mentioned tasks are the laminated elastomeric bearings and the sliding bearings, with multiple unique characteristics for each category.

e. Seismic isolation of structures or components in the vertical direction in addition to the horizontal directions is also feasible. This type of 3D isolation is generally achieved using appropriate devices with controlled dynamic stiffness in all three directions.
f. The expected increase in the seismic displacement response of the isolated structure implies specific design for the umbilical lines (distribution systems connecting isolated and not isolated parts; see Glossary).
g. The expected benefits of applying seismic isolation technologies for a nuclear power plant (NPP) or a nuclear facility are the following:
   - Seismic acceleration response of isolated SSCs is reduced. This reduction can be necessary to justify the design or decrease the costs of some SSCs in moderate and high seismicity areas.
   - Seismic design of SSCs can be standardized. It allows the installation of SSCs (with minimal design changes) on sites with higher seismicity than the standard design conditions.
   - Generally, uncertainties in the response of a seismically isolated structure are lower than those of a non-isolated structure. This is because the response, in the isolated directions, is primarily dominated by the isolation system, where the dynamic behaviour is well known. The uncertainties in soil and building behaviour are of secondary importance.

1.2.SCOPE

This publication presents the current state of practice and uses of seismic isolation systems in nuclear installations. The scope of this publication is limited to passive isolation systems and therefore the methodologies and considerations discussed are not applicable to active or semi-active seismic isolation systems.

1.3.OBJECTIVE

This publication develops the technical basis for the use of seismic isolation systems in nuclear installations. The objectives of this TECDOC are to:

a. Provide technical basis to support the revision of IAEA Safety Guides for new design and re-evaluation of existing facilities to include seismic isolation;
b. Assemble technical elements to cover design, risk or margin evaluation, manufacture, construction, and operation activities;
c. Present basic technical considerations for base-isolated nuclear installations, and structures, systems and components (SSCs) as reflected by the current state of practice.

1.4.STRUCTURE

Section 2 presents the general considerations in application of seismic isolation; including seismicity, definitions, and a description of existing nuclear design codes.

Section 3 presents general safety considerations.

Section 4 concerns design of seismically isolated nuclear installations.

Section 5 concerns beyond design considerations.

Section 6 presents seismic safety assessment.

Section 7 pertains to Quality Control and maintenance of isolation devices.

Section 8 introduces economic considerations of seismic isolation in nuclear facilities.

In relation to the objectives of this publication, as proposed in Section 1.1, the technical bases to support the revision of IAEA Safety Guides are discussed in Sections 3 and 4. Technical considerations covering design, safety assessment, margin evaluation, manufacturing, construction and operation activities are presented in Sections 5 to 9 and Appendix A. The whole publication presents basic technical considerations for use of SI technology in nuclear installations.

The most important base isolated nuclear projects are listed in Annex I. Annex II of this publication describes the isolation system implemented in these buildings. Annex III presents some cases which summarize satisfactory behaviour, where the information for the Tohoku earthquake is taken from reference [10]. Annex IV presents activities in different countries - France, Germany and Russian Federation, Republic of Korea, and Japan - related to design, implementation and R/D of base isolation for nuclear installations.

2. BASIC CONSIDERATIONS FOR APPLYING SEISMIC ISOLATION TECHNOLOGY

There are many benefits of seismic isolation in design and construction of new nuclear installations:

- Lower accelerations on structures and components, enabling simple, economical and standardised design.
- Simple structural behaviour leading to a simplicity of the analyses – in some cases, static analysis may be applicable for equipment inside an isolated structure.
- Increasing safety by decreasing uncertainties, due to the fact that the “critical” element is the seismic isolation system itself, for which the behaviour up to failure is better evaluated than that of a non-isolated structure.
- Simpler layout, with possibly more slender buildings and more flexibility to locate equipment. For example, due to almost constant acceleration over the height, it is possible to have heavy or sensitive components located at higher elevations.
- Cost reductions for new builds (in terms of scheduling and global price) due to the capability to reuse original design for middle range seismic input (typically 0.3g) and existing main components qualifications.

2.1. CONSIDERATIONS ON SEISMICITY AND SITE CHARACTERISTICS

As for any nuclear installation, site seismicity quantification is typically based on a good quality seismic hazard assessment, be it probabilistic seismic hazard assessment (PSHA) or deterministic seismic hazard assessment (DSHA). The site seismicity influences the amplitude, the frequency content and the duration of the earthquake signals affecting the structure. The amplitude of the site seismic response spectrum in the frequency range of the isolation system has a primary effect on the definition of the isolation system. It is worth noting that the seismicity characteristics, related to the low frequency content of the input signal, are different from the characteristics usually focusing attention for the design of a non-isolated structure; this requires specific information, developed in Section 4.1. As a consequence, it is recommended to use site-specific Ground Response Spectra (GRS), and not “general” GRS, which may not be suitable for low frequency content.

Site geotechnical conditions play an important role for base isolated structures. Rock and hard rock sites are preferable for the implementation of seismic isolation. Soft soil conditions may be challenging because:

- The performance of the isolation system may be decreased because of potentially high excitation at low frequencies and large induced displacements.
- The potential for differential settlement is increased, which may influence the distribution of vertical loads on isolators and may result in a heterogeneous loading of the isolators, or alternatively, in a very thick lower basemat. Care needs to be taken during construction, in order to prevent unnecessary initial differential settlement.
- Retention of soil pressure may result in thick walls to secure the space around the isolated building.

2.2. CONSIDERATIONS ON HORIZONTAL AND VERTICAL ISOLATION SYSTEMS

Horizontal isolation alone is the most common base isolation of a structure. It can be provided by different types of rubber or sliding bearings, with a low horizontal stiffness but a high vertical one. Attention has to be paid to the fact that, the isolation system may not be effective in the vertical direction, but some vertical stiffness and damping may exist and could be taken into consideration. In addition, the vertical excitation may induce a response of the structure in all three directions which is comparatively more significant than for a non-isolated case (see Section 4.1). Rocking effects may also become more significant in comparison to the non-isolated case. It can also happen that the rocking motions be effectively increased by the isolation system itself, due to the non-rigid vertical stiffness of the isolators.

Vertical isolation can be provided by spring type systems coupled to guiding devices allowing only vertical movement of the isolated structure or component. Such systems can typically be applied to isolate equipment sensitive to vertical excitation only. Attention has to be paid to the potentially significant vertical deflection of such system if subjected to variation of the vertical load, including self-weight, during normal or accidental conditions.

3D isolation can be achieved either with each isolator acting in three directions, e.g. rubber bearings with low vertical stiffness, coil springs with separate dampers, or, with two isolation systems in series, the first one acting horizontally and the second one vertically. The use of 3D coil spring isolators was proposed for some new design of NPPs [11] and the use of two systems in series was proposed for fast breeder reactors [12] with a global horizontal isolation of the plant and a specific local vertical isolation of the reactor vessel. In case of implementation of a 3D isolation system, specific attention has to be paid to the potentially increased rocking effect, which may challenge the overall efficiency of the system.

3. SAFETY CONSIDERATIONS

Basic safety considerations for seismically isolated nuclear installations need to be consistent with Safety requirements of the IAEA for design, operation and site evaluation (IAEA SSR-1 [2],SSR-2/1 [3], SSR-2/2 [4], SSR-3 [5] and SSR-4 [6]). The implementation of a seismic isolation system adds a new system for which safety conditions are defined and the compliance to applicable safety requirements is demonstrated. An important aspect from a safety point of view is the fact that the base isolation system is a safety system which is not redundant as a whole. In addition, it is generally composed of a large amount of almost identical components; the failure of one or a few of them is not allowed to influence the overall safety of the system. However, the latter may be not applicable to the isolation of a small building or equipment.

The four functions a base isolation system needs to ensure are: i) vertical supporting function, ii) isolation function by accommodating the displacement by stiffness, iii) displacement control by damping, and iv) re-centering capability (cf. EN 15129 [13]). An inspection programme of the isolation devices is to be defined, and an associated monitoring programme established. The base-isolated nuclear facility cannot be designed to be less safe and reliable than a non-isolated nuclear facility (both meeting the regulatory requirements and prescribed safety/performance goals for all design and beyond design cases). It needs to be robust enough and provide sufficient margin under design and beyond design conditions for earthquake and other external events, such as fire, flood, tsunami, aircraft crash, internal or external explosions, etc. [14].

This implies the following:

- The base isolation system safety requirements need to be translated to the isolation elements requirements and demonstration of compliance should be achieved.
- The seismic isolation system and its supporting structures need to exhibit adequate seismic margins to failure, for all design and beyond design loading cases, in compliance with the safety requirements of the isolated structure.
- The variation of characteristics of the isolation elements and of the isolation system need to be integrated into the design process and controlled at the manufacturing stage and throughout the operating life of the installation.
- The feasibility of replacement and adjustment of one or more isolators needs to be ensured throughout the life of the plant and needs to be considered at the design stage. The replacement cannot damage the isolators to allow further inspections and tests.

It is expected that the seismic isolation system has a restoring capacity by design and will bring the isolated structure back, close to its initial position shortly (within a few minutes) after an earthquake, so that the isolation system and structure maintain their seismic resistance to aftershocks. This expectation is an explicit requirement in JNES and French documents (Annex IV), and implicit due to the type of isolators considered in the NUREG/CR document [11].

3.1.PREVENTING FAILURE MODES OF SEISMICALLY ISOLATED NUCLEAR INSTALLATIONS

Failure modes of a seismic isolation system are presented hereafter, including adequate means of prevention of these failure modes ([15], [16] and Appendix A):

- Base isolation system failure modes:
    - Excessive displacement of **rubber bearing** isolators, with possible de-lamination of the bearing or rubber failure due to shear. This is prevented by determination of the failure limits of the bearings and implementation of design margin to this failure. It is possible to implement a hard stop in the isolation system design, so that failure due to excessive drift becomes geometrically impossible.
    - Excessive displacement of **sliding bearings**, with possible contact of the slider with the external surface of the bearing. This is prevented by the implementation of adequate design margin to failure. It is possible to implement a hard stop in the isolation system design, so that failure due to excessive displacement becomes geometrically impossible.
    - Buckling of isolators under combined vertical loads and horizontal drift. This is prevented by experimental determination of the buckling failure limit and implementation of design margin to this failure. Buckling can also be prevented by demonstration that no buckling of the bearing occurs before shear-compression failure.

- Excessive compression, with possible shear-compression failure of the rubber, or degradation of the contact surfaces of a sliding isolator. This is prevented by implementation of design margin to this failure.
- Excessive tension of isolator leading to shear-tension failure of the rubber. This may happen when overturning moment leads to significant tension in "corner" isolators or because of vertical earthquake excitation. Different approaches can be adopted to prevent this failure:
    - No tension is allowed to develop inside the bearings, either by requiring a minimum compressive stress in all design situations, or simply by allowing uplift to occur between the upper raft and the isolators. In the latter case, the consequences of the uplift need to be assessed and integrated into the design.
    - Determination of the shear-tension failure limit of the isolator and implementation of design margin to this failure.

  It is noted that sliding bearings do not allow uplift; therefore, their design needs to consider this situation if it occurs.

- Loss of bearing capacity due to an external event such as fire. This is prevented by using fire protected devices and/or avoiding fire sources near the base isolation system and by protecting the moat from external fires (e.g. in case of aircraft plane crash) with a specific structure (moat protective structure).

- Umbilicals failure modes

  Umbilicals are subjected to not only seismic acceleration but essentially to large support relative displacements during an earthquake. These large displacements may cause damage to umbilicals that are important to safety such as main steam-piping, cooling water/seawater piping, etc. To avoid this, either a specific layout is adopted in order to cope with differential displacements, or specific devices, such as angular expansion joints, may be included in the design.
- Substructure failure modes
    - Pedestal failures due to excessive loads transmitted to them.
    - Excessive loads on the raft at the pedestal junction
- Superstructure failure modes
    - SSCs located in the superstructure are usually designed to remain elastic under design seismic loading. Failure modes are usually related to drift; therefore, adequate margins need to be considered for beyond design conditions
- Isolated components
    - Large displacements for low frequency equipment, such as fuel handling devices, are typically explicitly examined and their design modified if necessary.
    - Sloshing of pools usually occurs at low frequencies and seismic isolation may increase sloshing loads.

3.2.MONITORING OF ISOLATORS CHARACTERISTICS VARIABILITY

Isolators' mechanical properties have inherently more variability than conventional structural parts. Variability may arise during manufacturing (for example, rubber properties depend on the vulcanization duration for rubber bearings or friction coefficients for sliding bearings). Variabilities may also arise during construction (geometrical tolerances during installation of isolators affect the global properties of the isolation system), during operation (ageing process), during an earthquake, or other accidental loads (characteristics change due to the loading or due to cycling, for example lead plugs will heat up under repeated loading cycles and change characteristics). Variability due to ageing is controlled by in service inspection, as described below, and manufacturing and construction variabilities are managed by QA manufacturing and construction procedures, the variability due to loads and loading cycles is managed through test programs.

All types of base isolation systems exhibit, more or less, changes in mechanical properties with time (ageing process). These variations of properties need to be properly accounted for in the design by defining bounding values and performing the design analysis with these bounding values.

As a consequence (or additionally), it is necessary to monitor the mechanical properties of isolation system during the entire life of the facility, in order to check the ageing process and in order to confirm that the actual values remain within the bounding values assumed in design.

The management of ageing varies from member state to member state; it can involve a combination of accelerated ageing material tests, in-situ material tests and full-scale seismic isolators test.

For metallic parts, corrosion and relaxation needs to be monitored. For dampers, oil and similar products may be subjected to ageing and their characteristics are periodically tested and controlled.

3.3.REPLACEMENT PROSPECT

In order to cope with possible degradation of isolators, feasibility of replacement of one (or several) seismic isolation element(s) is usually required by Regulators. The need for such replacement could be the verification of properties of one or several systems to determine if properties are outside the design limits; the isolators have experienced accidental damages, an excessive deterioration of mechanical properties due to ageing or due to a strong external load –earthquake or other – or a change in seismic demand requiring new isolators. If the two latter cases are suspected and determined to be the cause of property changes, it is likely that almost all isolators may need to be replaced.

The replacement of one isolator needs to be considered in the design. As an example, in the French EDF NPP located in Cruas, replacement of two isolators was effectively carried out (AFCEN [17]) in the 90's.

The replacement requirement in conjunction with inspectability, needs to be taken into account at an early design stage, as it will have an impact on the design of the substructure and the seismic isolation story. Moreover, the number of isolators located on a pedestal need to be limited and the distance between pedestals has to allow for inspection and replacement activities. In addition, it is often required [11] and [17] that the upper raft, with the appropriate load combinations, be designed for at least one missing support or isolator.

4. SEISMIC ISOLATION DESIGN

4.1. DESIGN CODES AND TECHNICAL DOCUMENTS FOR SEISMIC ISOLATED SYSTEMS

Design codes for conventional seismically isolated structures

Some design codes developed for conventional seismically isolated structures are presented in this subsection. They have been used as the basis for design of isolated nuclear structures as well. Seismic isolation elements covered by these codes are the same as those used in nuclear facilities, with the exception of the dimensions of the devices (generally larger for nuclear facilities).

- ASCE/SEI 7-16 Minimum design loads and associated criteria for buildings and other structures, American Society of Civil Engineers (ASCE), 2016 -USA [18]

- AIJ, Recommendation for the Design of Base Isolated Buildings, Architectural Institute of Japan, 2013. (in Japanese) [19]

- JSSI ([20], [21], [22]) Japan Society of Seismic Isolation developed texts giving list of possible devices, Guidelines for umbilical's design and elements on maintenance for buildings and bridges.

- EUROCODE 8:

  EN 1998-1:2004 – Eurocode 8: Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings [23]

  EN 1998-2:2005 – EUROCODE 8: Design of structures for earthquake resistance – Part 2: Bridges [24]

  These codes are used for conventional structures in Europe, together with the following standards, specifically dedicated to seismic isolation devices design:

  EN 15129:2010 – Anti-Seismic Devices [13]

  EN 1337:2005 – Structural bearings [25]

  These codes are specifically adapted for the design of isolated nuclear facilities in France at RJH and ITER.

ISO22762 [26]: This international Standard is dedicated to elastomeric seismic isolators. Part 1 specifies the test methods for determination of the characteristics of elastomeric seismic isolators and for measurement of the properties of the rubber material used in their manufacturing. Part 2 describes applications for bridges and Part 3 is for building applications. This document presents a complete set of guidance for determination of isolators' properties (Low Damping Rubber Bearing (LDRB), High Damping Rubber Bearing (HDR), Lead Rubber Bearing (LRB), etc.) based on tests. Many independent national standards are based on this document.

Available technical documents for nuclear installations

There are multiple general documents devoted to the seismic isolation of nuclear installations. Only one, from Japan, can be considered as a design code, or more precisely, an application document for design:

- **JEAG 4614-2013, Seismic Design Guidelines for Base-Isolated Structures of Nuclear Power Plant, Japan Electric Association, 2013.** [27]

The guidelines specifically describe design methods and procedures of seismic isolation such as calculation of design basis seismic force, design of isolation device, design of SSCs of base-isolated NPP, quality control, etc. The guidelines are based on JEAG 4614-2000 and revised to meet the requirements of the Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities (Nuclear Safety Commission, 2006). In addition, the guidelines are revised considering the consistence of the design methods with Technical Code for Seismic Design of Nuclear Power Plants (JEAC 4601-2008, Japan Electric Association, 2008). This document is in Japanese, and no official translation exists at this time.

- **European Commission, Proposals for design guidelines for seismically isolated nuclear plants, EUR 16-559 EN, 1995.** [28]

This is a first proposal for the development of guidelines for the use of seismic isolation for nuclear installations. A revision of the document was issued in 1998 in order to integrate 3D systems and rolling ball-dissipative layer systems, both developed in the Russian Federation. The development of these two systems was discontinued. The initial document provides general information with few specific details, but does not provide much justification.

- **AFCEN French Experience and Practice of Seismically Isolated Nuclear Facilities**

The most recent designs of base isolated nuclear structures are the RJH research reactor and the ITER international project, both under construction in Cadarache, France. The design of these isolation systems did not rely on a single specific code but on a combination of the European codes described above and best practices developed by the French industry based on 30 years of return of experience in design, construction and monitoring of seismically isolated nuclear installations. The main elements of these practices and experiences have been included in the design document for Civil Works [17]. Annex A of Ref. [17] summarizes the main requirements of the document. It applies to the seismic isolation of a building or a complete installation. Some specific features are as follows:

- The material used for elastomeric isolation devices is synthetic rubber called poly-chloroprene (CR bearings), which has a long industrial history of manufacturing bearings in Europe.

- Higher margins are proposed for design as compared to the design of conventional non-nuclear structures. For instance, the maximum allowed seismic distortion is 1.4 for nuclear, compared to 2.5 for the conventional applications. Additionally, a minimum compressive capacity of 1 MPa is also required for non-anchored bearings.

- The effect of ageing on the mechanical properties of the isolators is determined based on measurements made on both, samples and actual bearings taken out from existing isolated nuclear installations. These samples and actual bearings have experienced 30 years of ageing in actual environmental conditions.

- Specific requirements for quality control and maintenance of isolation devices are described for all stages of construction of the installation.

- Tolerances for the setting of isolation bearings are proposed based on the return of experience of the RJH and ITER projects.

- Some recommendations on the analysis methodology to generate floor response spectra are given in order to capture the possibility of significant peaks at higher mode frequencies.

- **U.S. Nuclear Regulatory Commission (USNRC) NUREG/CR-7253, Technical considerations for Seismic Isolation of Nuclear Facilities, 2018.** [11]

This is a document which gathered technical elements on base isolation in order to prepare the drafting of a Safety guide on this subject by US NRC staff; it is not a regulatory document. The document addresses all relevant points, even if some parts are only briefly mentioned, (for example: structural analysis refers to other relevant documents in US, such as ASCE-4 [29] or ASCE-7 [18] or ASCE/43-05 [30]). The document develops a full performance-based and risk-informed design philosophy. The guidance mainly focuses on horizontal isolation of nuclear islands, composed of reactor building, nuclear auxiliary buildings and possibly other parts of the plant. Isolation of components is addressed to a limited extent. The main features addressed in the documents are as follows:

- The document addresses isolators common to US industry practice:
  - Low damping natural rubber bearings
  - Lead-rubber bearings
  - Spherical sliding bearings

  The document doesn't cover other types of bearings used in different countries, such as high damping rubber, synthetic rubber, or 3-D isolation; these systems are only acknowledged, despite the fact that some are used extensively in other countries.

- From a safety analysis point of view, specific points are related to the particular situation of the isolation system, which is a non-redundant safety related system. Therefore, it needs to have more stringent design criteria than more conventional construction. The isolators cannot be allowed to fail and need to be removed from any realistic sequence of potential failure of the plant due to earthquake shaking.

- The potential for cliff edge effects is to be removed through the use of a hard stop.

- Recommendations for the design of the moat gap are suggested.

- A passive re-centring system can be included.
- Performance criteria are proposed based on performance-based approaches described in ASCE 43-05 with some adaptations. In addition to the Design Basis Earthquake, for

which the same criteria as for non- isolated plants are applied, an Beyond Design Basis earthquake is defined with a 100,000-year return period. It is to be at least equal to 1.67 times the Design Ground motion. For the Beyond Design Basis Earthquake, ultimate requirements for the isolation system are proposed in Table 8-1 of Ref [11].

- Three options for structural analysis are mentioned: 1) coupled time domain, 2) coupled frequency domain, and 3) multi-step. Coupled 3D time domain modelling has no usage restrictions, coupled frequency domain can only be used with low damping rubber bearings (essentially linear) without damping and, in certain limited circumstances, to provide input to the multi-step method.

- Tension or uplift of the superstructure relative to the isolators is allowed, provided that their effects are correctly taken into account.

- Assurance of performance needs to incorporate a combination of prototype and production testing to physically demonstrate quantifiable confidence levels and performance reliability in both the isolators and the umbilicals.

- **ASCE Standard, ASCE 4-98 Seismic Analysis of Safety-Related Nuclear Structures and Commentary. ASCE, 1998**

This document is the basis for the analysis of nuclear structures in many countries. There are very few specific elements for base isolated nuclear structures: some very general elements are provided in Section 3.5.6. The revision of this document includes more specific data for Isolated Structures, with a performance based approach coherent with ASCE 43-05.

- **ASCE Standard, ASCE 4-16 Seismic Analysis of Safety-Related Nuclear Structures and Commentary. ASCE, 2017** [29]

This document is the revised version of ASCE 4-98 and includes guidance specific to seismically isolated structures in Section 7.7.

- **JNES, Seismic Safety Division, Proposal of technical review guidelines for structures with seismic isolation, report n° JNES-RC-2013-1002.** [31]

This report is the first complete edition of a document which was drafted by JNES, the former Technical Support Organisation to the Japanese safety authority and presently integrated inside Nuclear Regulation Authority (NRA) to give guidelines for the review of projects of seismically isolated nuclear installations. It is specifically intended to be usable by different countries, covering a large variety of installations in low to high seismicity regions. The document covers building and floor or equipment isolation. For each subject, the document defines the principles and provides a commentary which gives more detailed information. There are few numerical prescriptions, but more general definitions of requirements for which specific values are defined by the designer. Some features of this document are:

- The document does not recommend a specific type of isolation system, but general indications are given in order to define criteria for each system
- New and existing facilities are considered; for the latter, only equipment or floor isolation is suggested

- Horizontal and vertical systems are included

- Seismic structural analysis methods are similar to non-isolated ones

- Beyond design and margin considerations are treated in the framework of residual risk assessment, following the 2006 Japanese seismic regulatory document. No additional guidance is proposed.

- The entire plant life is covered, including the definition of tests and inspections during the pre-operation phase, operation phase and ageing management, and performance tests after an earthquake.

- The document is supplemented by examples of seismic isolation trial design and preliminary assessment for nuclear buildings (Pressurized Water Reactors (PWR) and Boiling Water Reactors (BWR)), equipment isolation (computer system, floor supported system), design of connecting piping systems and design of equipment in a BWR. In addition, some papers on fragility estimation of components are included.

An abridged version of the document is included in the Annex IV of this publication.

4.2.DESIGN BASIS EARTHQUAKE AND INPUT GROUND MOTIONS

The Design Basis Earthquake needs to be established per IAEA Safety Standards with appropriate considerations of local site conditions.

For seismically base isolated structures, the following elements are considered explicitly in the development of a Design Basis Earthquake, which is typically represented by a ground motion response spectrum and/or ground motion time series.

- A range of frequencies that includes the effective period of the isolation under a ground motion representing the design basis earthquake with appropriate margins. The effect of velocity pulses that may result from large magnitude earthquakes at small site-to-source distances ([32], [33])
- The duration of strong ground motion, which affects the response of nonlinear isolation systems sensitive to cycling loads. It should be noted that high magnitude earthquakes far from the site generally have a very long duration [34].

If three-component acceleration time series are used for analysis, it needs to be ensured that the records are consistent with the Design Basis Earthquake. Information on the generation of time series can be found in IAEA Safety Guide SSG-9 [7], NIST GCR 11-917-15 [35], ASCE 4-16 [29], and Japanese NRA Regulatory Requirements [36].

4.3.DYNAMICS OF SEISMICALLY ISOLATED STRUCTURES

The seismic response of an isolated structure can be described by the following elements:

- In the directions of isolation, assuming linear behaviour of the isolation system, the isolated structure response is dominated by its first mode. For an efficient isolation system, this first mode corresponds to a deformation of the isolation story and a quasi-rigid translation of the superstructure.
- For nonlinear horizontal isolation systems, the effective isolation period varies as a function of horizontal displacement. The response of the superstructure is a function of the hysteretic characteristics of the isolation system.
- For linear horizontal isolation systems, the horizontal acceleration response of a stiff superstructure is approximately constant if the effects of rocking are small. The horizontal response in a given direction is roughly equal to the horizontal spectral acceleration in that direction at the frequency and damping of the isolation system. The displacement response in a given direction is approximately equal to the horizontal spectral displacement in that direction at the frequency and damping of the isolation system.
- For nonlinear isolation systems, the use of a ground response spectrum is not appropriate to predict the response acceleration and displacement of the isolated structure, even if it can give a first order of magnitude. For such systems, nonlinear response-history analysis is to be used to compute the response of the superstructure. For the purpose of analysis, three-component time-history ground motions need to be selected and scaled to be consistent with the input spectrum. The response is significantly dependent on the characteristics of these time histories, such as the strong motion duration, or presence of a velocity pulse at low frequencies ([32], [33]).
- The isolators of the isolation system are typically modelled explicitly in the mathematical model to capture the effects of torsion and rocking of the superstructure.
- The isolation system translates and rotates in response to the seismic inputs and the distributions of mass and stiffness in the isolation system and superstructure. The effects of torsion and rocking on the isolators is greatest at the periphery of the isolation system. The torsional response can be mitigated by the placement of the stiffest isolators at the perimeter of the isolation system. Rocking of an isolated structure, if important, can be mitigated through the addition of vertically stiff damping devices. It can be taken into account that an increase in damping will decrease the relative displacement between isolated and non-isolated parts but may have detrimental effects on the superstructure response ([37], [38]).
- The three-dimensional response of the isolation system and isolated superstructure need to consider all three components (two horizontal and one vertical) of seismic input. The geometry of the isolated superstructure may result in coupling of horizontal and vertical modes of response in the superstructure [39].

4.4.TYPES OF ISOLATION SYSTEMS

The choice of an isolation system is a function of the seismic demand (see Design Basis Earthquake in Section 4.2), site conditions (soil, temperature, environment, etc.), weight of the isolated structure, and its expected seismic response. The choice needs to rely on industry experience in the country of application and in the country of manufacturing of the isolators.

The type of isolation elements that can be assembled to form a seismic isolation system is chosen based on the loading conditions at each of the isolators.

Except for active and semi-active isolation systems (see Section 1.2), there is no restriction to the type of technology that can be used, provided that it meets the safety requirements and that its characteristics are fully determined by an appropriate test program, including quantification of all possible variabilities.

4.5.ELEMENTS OF ISOLATION DEVICES

This section provides basic information about seismic isolation elements used or considered in the design of nuclear installations. These elements, alone or assembled, constitute the seismic isolation device which provides the needed isolation function. Table 1 presents, in a simplified way, a possible classification of isolation elements. There are two categories of isolation devices: the first one is bearing devices, which generally have the function of bearing (supporting the weight of the isolated structure or equipment) and of filtering seismic excitation, the second category is dampers, which have the function of adding damping to the system in order to limit the drift of the isolation system.

A large variety of devices exist. All are not suitable for nuclear installations which are safety related and required to have a long design life. In addition, certified materials are typically used for isolation devices. A detailed description of isolation devices is presented in Appendix A.

TABLE 1. CLASSIFICATION OF BASE ISOLATION DEVICES

<table>
<tr><td rowspan="4">Bearing Devices and Elements</td><td>Laminated Rubber Seismic Isolation elements:
A. Low Damping Rubber Bearing
B. Lead Rubber Bearing
C. High Damping Rubber bearing</td></tr>
<tr><td>Sliding elements
A. Rigid Sliding Bearing
B. Elastic Sliding Bearing
C. Friction Pendulum System</td></tr>
<tr><td>Coil Springs</td></tr>
<tr><td>Other</td></tr>
<tr><td rowspan="2">Dampers 1D, or Multi-Directional</td><td>Hysteretic Damping type
A. Steel damper
B. Lead damper</td></tr>
<tr><td>Viscous damping devices
A. Oil devices
B. Viscoelastic type</td></tr>
</table>

4.6.LAYOUT OF ISOLATORS

The following considerations establish the design of the isolators' layout:

a) It is recommended that vertical loads are homogeneously distributed on the bearings (Ref. [17], [23] and [24] specify an allowable variation of loads between different isolators of ±20%). This limits the flexural stresses in the basemat and differential behaviour between isolators that might depend on the vertical load (for example, friction forces). Soil settlement is to be considered when assessing the distribution of vertical loads on the bearings.

b) Offset between the rigidity centre of the isolation system and the gravity centre of the superstructure (eccentricity of the seismic isolation system) is to be limited to a value as low as reasonably achievable, in order to minimize the torsion phenomenon. The torsion phenomena can also be mitigated by the placement of stiffer isolators at the perimeter of the isolation system.

c) Rocking motions of an isolated structure need to be considered as part of the layout design. If significant rocking could be mitigated through addition of vertically stiffer damping devices at the periphery of the basemat.

d) To prevent load transfer through the basemat (which complicates its design and increases the uncertainty in calculation of the bearing reaction loads and reduces the potential of rocking induced by vertical excitation), isolators can be located directly below the vertical structural elements: walls or columns, where possible and achievable.

e) The layout needs to ensure the ability to inspect and replace any of the individual isolators. For isolated buildings, this consideration implies sufficient space all the way around, or at least on one side of the isolators, to support replacement activities. Circulation paths through the inter-basemat space are also to be arranged to allow for insertion and removal of isolators and tools necessary to perform the replacement.

4.7.ANALYSIS METHODOLOGIES AND MODELLING OF A SEISMICALLY ISOLATED STRUCTURES

Analysis methods for seismically isolated structures are basically the same as those used for non-isolated ones [40]. Some points requiring specific attention are summarized hereafter:

a) The superstructure is usually represented by a 3D model with sufficient details to capture rocking and torsional motions of the superstructure as well as any other local coupling effect between the directions of excitation (as highlighted in Section 4.3).

b) For non-linear isolation systems, response evaluation of the base-isolated structure is typically performed by time history analysis, accounting for the system's non-linear behaviour. The excitation is typically applied simultaneously in the 3 directions.

c) For linear isolation systems with low damping, modal response spectrum methods can be used. Time history analysis, possibly by modal superposition, remains the preferred method, at least to generate in structure response spectra. The excitation is typically applied simultaneously in the 3 directions.

d) The model usually allows for a precise evaluation of the reaction forces and of the possible uplift on each isolator individually. Therefore, the positioning of the isolators below the superstructure in the model needs to be realistic.

e) The isolators' properties inserted into the analysis model such as force-displacement relationships (horizontal and vertical) and/or damping properties are always based on representative tests of the products.

f) The variability of the isolators' properties due to ageing, loading, cycling, temperature, environment condition, manufacturing, installation or others, need to be either explicitly included into the analysis model or covered by performing boundary cases analyses in the design process.

g) Soil-structure interaction effects are usually included into the model, except if demonstrated to be insignificant. These effects are generally negligible for an isolated structure on a hard rock site, though only in the directions of isolation.

h) Attention should be paid to the modelling of the superstructure structural damping in case of performing non-linear time history analyses. In particular, the use of a complete Rayleigh damping for the superstructure is incorrect, because the damping term resulting from the mass matrix would spuriously damp the "rigid body" motion of the structure on its isolation system. Possible alternatives are to use modal damping for a linearly modelled superstructure or to develop a specific damping matrix applied to the velocity of the superstructure relative to the basemat [41].

i) For analyses using in-structure response spectra, the horizontal and vertical seismic loads are typically combined by appropriate methods considering the vibration characteristic of the base-isolated structure. SRSS is not always appropriate for modal combination because, very low and medium frequency signals are cumulated, for which maxima generally cannot be considered as independent, and because medium frequency responses can be in-phase and need to be cumulated algebraically. In general, Newmark combination for directions is acceptable.

4.8.ANALYSIS AND DESIGN OF SEISMIC ISOLATION SYSTEMS

The design of the seismic isolation system typically ensures that the allowable design limits are respected, with due consideration of the variability of the isolators' characteristics, when applying the design input ground motions to one or several analysis model(s) of the structure [42]. Details of the analysis and design process for the seismic isolation systems are presented in the following sections of this TECDOC:

- Section 4.2 for the definition of the Design Basis Earthquake and the generation of the input ground motions
- Section 4.3 for an overview of the dynamics of a seismically isolated structure
- Section 4.7 for the appropriate analysis and modelling methodologies
- Section 4.12 for the definition of the design allowable limits for the isolation system

One important characteristic of almost every base isolation system is its nonlinear behaviour: sliding, non-linear elasticity, non-linear damping behaviour, etc. As a result, linear analyses approaches, such as conventional modal response spectrum methods, are not directly applicable, at least without some adaptation for analyses of structures, isolation systems, and for floor response spectra derivation. In addition, non-linear behaviour requires the use of more time-histories than a conventional linear time-history approach. Simplified approaches, such as equivalent linearization, may be applied in some cases; however, they need to be carefully validated. Another question raised by this fact is, for example, that linear combination is not strictly applicable, for extrapolation of results with a stronger input. Specific attention should be paid to design representation of non-linear damping and its computation [43].

4.9. ANALYSIS AND DESIGN OF SUBSTRUCTURE AND SUPERSTRUCTURE

As for any other structure, the substructure and the superstructure are to be designed based on recognized codes and standards. It should be noted that some topics, specific to the design of seismically isolated buildings require special care:

- The lateral walls of the substructure, bearing soil pressure loads in normal and seismic conditions, is to be designed with a reliability that is at least equal to that required for the seismic isolation system itself (Section 3.2).
- The pedestals or walls supporting the isolators is to be designed with a reliability that is at least equal to that required for the seismic isolation system itself. Seismic capacity of the substructure and isolators system is to be coherent and adequate capacity design is to be applied.
- The superstructure is to be designed to remain in its elastic range for the design basis earthquake and, as far as reasonably achievable, for the beyond design earthquake loadings as well. Because of the low frequency content of the excitation transmitted by the seismic isolation system, the ductility of the superstructure does not provide margins comparable to the ones obtained for a non-isolated structure ([44], [45]). This point is only indirectly mentioned in seismic codes for conventional structures by limiting the behaviour coefficient of the superstructure to a value close to 1. For nuclear installations, ductility coefficients are to be considered with extra care. Furthermore, an additional margin can be applied to SSCs. Many nuclear power plant projects are basically designed for minimum seismic conditions (around 0.25g-0.30g ground acceleration), with the possibility of base isolation for sites with higher seismicity. This design procedure provides generally sufficient margins to cope with the increased ductility demand.

4.10. ANALYSIS AND DESIGN OF INTERNAL SSCS

The analysis and design of equipment and other SSCs installed in an isolated structure typically follow procedures used for non-isolated structures, recognizing that the use of an isolation system will alter the shape and ordinates of floor response spectra and the frequency content of floor input signals. Therefore, coefficients used in modal analysis of an isolated SSC with complex quadratic combination (CQC) method, are adapted to be consistent with the isolated structure.

Although the use of isolation will generally substantially reduce horizontal spectral demands [16], longer period parts of equipment such as arms on fuel handling machines may experience greater demands and re-qualification may be required.

Qualification may involve an earthquake simulator and significant long period spectral demands may be difficult to achieve in commercial test facilities. Thus, supplemental methods may be required to demonstrate adequate long period capacity. If the pseudo acceleration value of the floor response spectra is below 1g, static testing of the equipment with an angle to the vertical axis could replace a dynamic test.

Fluid in spent fuel pools and tanks excited by earthquakes may slosh, with wave heights varying as a function of pool/tank geometry, use of baffles, and seismic input. Wave heights may be exacerbated by the use of seismic isolation and more freeboard may be required.

Floor response spectra in the superstructure may present a significant peak at the frequency of the fixed-base superstructure. This may be due to a high damping in the isolation system, rocking of the foundation by kinematic interaction, coupling between vertical excitation and horizontal response (when plant geometry is complex), or other phenomena [46].

Lastly, it is recommended not to account for any ductility factor in the estimation of the beyond design behaviour of the internal SSCs. This is because a significant part of the seismic demand is at very low frequency (compared to the frequency of considered SSCs) and can be considered as pseudo static for most components.

4.11. ANALYSIS AND DESIGN OF UMBILICALS

Piping, cable trays, air ducts, and electric wire pipes are possible crossover components between base-isolated and non-base-isolated structures. They are defined as the umbilicals of the isolated structure. They can potentially be subjected to large differential displacements and need to maintain their required safety function during a design base earthquake and beyond design situations. These components are to be designed to have enough margin against allowable design limit displacements and maintain required safety functions during design base earthquakes and beyond design situations. They are therefore designed in accordance with the allowable limits set for the isolation system in Section 4.12.

Routing arrangements of pipes or utilizing expansion joints are possible measures against the large relative displacement of interface area. Not only relative displacement, but also seismic acceleration, service conditions such as temperature and internal pressure, and aging degradation are typically important to the design of those components. In cases where expansion joints are used, reliability needs to be confirmed by testing. Reference [47] contains examples and photos of shaking table tests.

In cases of equipment isolation, crossover components between seismically isolated equipment and non-seismically isolated structures cannot be allowed to significantly influence the seismic isolation function of the isolated equipment. The following are inappropriate examples of crossover structures:

- Crossover components installed in close proximity to the base-isolated structure can cause torsional motion of the superstructure during an earthquake.
- Friction between the interface floor and base-isolated equipment can affect movement of the isolation devices.

Obstructive objects need to be prevented from colliding with isolated structures during earthquakes.

4.12. DESIGN ALLOWABLE LIMITS FOR THE SEISMIC ISOLATION SYSTEM

Design allowable limits are determined as to fulfil the basic performance requirements for seismic isolation (Section 3), considering all possible failure modes of the seismic isolation system (Section 3.1) and considering the variability of the isolators’ characteristics (cf. Section 3.2).

Design allowable limits are technologically dependant. Their values are to be set on a case by case basis and supported by experimental demonstration of the adequacy of the allowables.

Design limits include:

- Maximum allowable displacement (examples: shear strain limit in a rubber bearing, coil contact for a spring, ultimate displacement for a sliding bearing, contact with the surrounding infrastructure for any kind of system)

- Maximum allowable combination of displacement and normal loads (example: shear-tension in a rubber bearing, buckling phenomena)

- Maximum allowable uplift or impact force after uplift, if applicable to the selected technology.

Moreover, additional design allowable limits could be set if there is a necessity to limit the variation of a certain characteristic of the isolators. As an example, a limit on the lead heating within an LRB during the seismic event could be set if such limit is found necessary to avoid reaching another of the allowable limit (possibly displacement in that example case).

4.13. CONSIDERATIONS FOR NON-SEISMIC EXTERNAL HAZARDS AND LOADS

Seismic isolation systems are typically designed considering the following external loads (besides seismic loads) ([14], [40]).

- Wind loading,
- Lightning (connections needed for grounding),
- Tsunami,
- Flood,
- Aircraft impact,
- Man induced external explosions,
- Slope collapse,
- Fire.

In cases of building isolation, avoiding flooding in the isolation device area is desirable. Fluid forces and buoyancy due to flooding may affect the function of the seismic isolation structure. Flood induced debris could also cause malfunction of the seismic isolation system.

Concerning external events to the whole facility, such as aircraft impact, man induced external explosions, or extreme wind loading, the structures are designed as fixed base structures subjected to the same external event. The slab and wall thicknesses and reinforcement details of the structures need to be identical. Structural inertia of major nuclear buildings, during the loading time, is generally identical to that of a fixed base model. However, once the primary load subsides, the isolated structure responds at a low frequency. Kinematic effects of the facility on the isolation system are be computed and their impact, on isolators and structures, assessed. In such analyses, the radiative damping in the soil, which may be significant for a fixed base structure, will not be present, at least in the horizontal direction. Only the isolator system damping may be mobilized, which may result in lower modal damping than for non-isolated structures. This may influence the induced floor response spectra.

In addition, it is important to protect the seismic isolation story (space below the upper basemat, where the isolation system is located) by a moat protecting roof in order to avoid the intrusion of burning kerosene or other flammable liquid from the outside. Local fire protection of each isolator may also be considered as an alternative.

5. BEYOND DESIGN BASIS SEISMIC EVENTS

Responses during beyond design basis seismic events are to be examined. A typical characteristic of a seismically isolated structure is that the demand on the isolation system itself, due to increased displacements, increases faster than the demand on the isolated SSCs, which are protected by the isolation system. The adequate determination of the response of the isolation system to beyond design basis earthquake is, therefore, of primary importance.

Two alternative paths could be followed for examination of the isolated structure's response during a beyond design basis seismic event:

(a) Having sufficient margin in the design of the isolation system so that the residual risks for the beyond design basis seismic motion is demonstrated to be sufficiently low. This approach needs to be consistent with the related publications on seismic risk analysis issued by the IAEA and/or other authorities; or
(b) Implementing a hard-stop, limiting larger than specified responses and assuring stability and safety of the isolation system per Ref. [11] and [29]. These documents do not consider the effects on the superstructure due to impact with the hard stop.

The presence of a base isolation system has a very significant effect on beyond design verifications. Seismic isolation is a large set of similar isolators mounted in parallel, where all elements behave in a similar way, and a common or cascading failure could be plausible. As a consequence, additional margin and/or supplemental features are needed for the isolation system, in the framework of beyond design considerations. On the contrary, failure of one or few isolators will not typically result in catastrophic failure.

Treatment of beyond design conditions is still under development around the world and a common approach has not been developed or found.

The USNRC text [11] requires a hard-stop around the moat. A design consideration raised by the proposed approach would be the dimension of moat and the design of the hard-stop system. Table 1 of Ref. [11] shows the features for design of a hard-stop system with beyond design basis corresponding to a seismic event with a 100,000-year return period. This event is, from the consideration of probabilistic safety analysis, sufficiently rare so consideration of the effect of impact, of a hard-stop system, generating unfavourable responses, on the isolated structures and components is not required.

French practice relies on the significant margins taken in the rubber bearing for the allowable strain under seismic load, 140% or lower, when test results can show an acceptable behaviour up to 300% for the commonly used LDRB.

It is noted that the ultimate behaviour of the whole seismic isolation system needs to be considered, including pedestal, lower basemat, and connections of the isolating system (i.e., rubber bearings and/or damping devices (if any)) to the base-isolated structures. Typically, the ultimate behaviour of all the components is compatible.

For rubber bearing systems, not fixed to the upper and lower rafts, instability effects (such as roll over) can be observed after some distortion. It is not clear, however, if such situations might lead to a “failure”. Another possible failure mode which is to be considered is uplift of or tension in an anchored bearing. A clear depiction of these ultimate behaviours has not yet been observed. Some other effects, such as kinematic interaction and wave propagation [46], may also have an effect on margin assessments.

For sliding bearings, the maximum relative displacement between the upper and lower plate is limited by construction. When treatment comparable to the moat width definition is applied larger devices may be necessary.

Both umbilical and cross-over structures requested for this case, need to be designed to cope with the displacements induced by beyond design basis seismic conditions.

Few documents mention the non-linear behaviour of isolated structures. In addition to the papers by Politopoulos [47] and Huang et al. [40], Thiravechyan [48] gives results of a simplified two-degree-of-freedom system. The analysis results confirm the large inelastic demand in the superstructure. There are no published results of non-linear responses of a seismically isolated detailed 3D model structure.

However, as mentioned in Section 4.2, for SSCs located above the seismic isolation system, the ductility demand, in case of non-linear behaviour, is significantly higher than for the same SSCs located in non-isolated structures.

6. SEISMIC PROBABILISTIC SAFETY ASSESSMENT FOR NUCLEAR INSTALLATION SEISMIC ISOLATION SYSTEMS

Methodology for performing SPSA is presented in SSG-3 [49] and NS-G-2.13 [9]. Consideration of specific aspects related to seismic isolation system in SPSA are addressed in the following tasks:

- Structural response analysis affecting calculation of seismic demand for the isolated parts (addressed in seismic fragility). SSCs ultimate behaviour estimation, taking into account the specific input signal characteristics of the isolated superstructure.
- Umbilicals capacity: if safety significant components’ seismic capacity is controlled or influenced by the umbilicals (addressed in seismic fragility).
- Consideration of specific failure modes of the seismic isolation system (SIS) as a whole, or deterioration of SIS performance – if not screened out, it is to be included in the SPSA model (addressed in seismic fragility and system analysis).

The SPSA end products are seismic insights derived from:

- Systems model and accident sequences analysis results,
- List of risk significant SSCs,
- Dominant accident sequences, and
- Quantitative results (such as core damage frequency (CDF), and large early release frequency (LERF), or other undesirable end states frequencies (mean values and probability distributions of the end state frequencies)).

SPSA can be used to verify/confirm the seismic robustness of the design including the seismic isolation system, and in further stages to check if the ‘as built’ and ‘as operated’ facility meets the target performance goals associated to the seismic hazards. SPSA also helps to identify potential seismic vulnerabilities and/or safety improvements that may further reduce the seismic risk of the nuclear facility. It is expected that for a well-designed seismic isolation system the SPSA results will show:

- Low contribution of the seismic isolation system to the seismic risk (CDF/LERF).
- The overall seismic risk of the facility with a seismic isolation system is significantly lower than the un-isolated equivalent on the same site.

7. QUALITY CONTROL AND MAINTENANCE OF ISOLATION DEVICES

This section highlights the technical requirements for the isolation system and, by extension, for the peripheral components such as umbilicals.

7.1. TECHNICAL REQUIREMENTS FOR DESIGN STAGE

Due to the non-redundancy of the system, the seismic isolation system is typically sized with adequate margins to ensure the basic safety functions developed in Section 3.

In addition, the design robustness of the isolators themselves is considered as follows:

- Each specific project’s environmental constraints are to be taken into account for the selection of the best isolator technology and associated equipment or support. Attention should be paid to the consequence of some design choices which could become technical requirements (e.g erection sequence, casting method).
- The behaviour of the isolators is to be tested (full-scale) in order to determine the main mechanical properties of the seismic base isolation system. For beyond design behaviour, if full-scale test cannot be performed, scaled models, whose representativeness is demonstrated, can be used for the safety demonstration.
- The structure’s response influence is to be retrospectively checked in the margin of the isolator (variation of vertical loading, imposed rotation due to rocking, etc.). The subtlety lies in the interdependence between the base-isolated structure design and the isolator design itself.

7.2. TECHNICAL REQUIREMENTS FOR PROCUREMENT STAGE

Isolators need to have an adequate quality assurance and quality control in order to ensure the durable basic safety functions developed in Section 3.

The control of the production relies on manufacturing control during procurement and manufacturing is validated through mechanical testing of the final products. The existing various standards in the conventional field (non-nuclear installations) can sustain the quality approach (e.g. EN 15129 [13], EN 1337 [25], ISO 22762 [26], ASCE 4 [29], etc.) but need to be identified according to safety guidelines (such as IAEA GSR Part 2).

It is strongly recommended that a dedicated quality and control plan identifies the traceability of the material and, for each activity, the surveillance actions (before and during production in the form of an audit or review). The goal of the plan or procedure is to demonstrate satisfactory management of the manufacturing processes.

The implementation of the plan needs to consider the following main but non- limitative points:

- The definition of controls and tests to be performed on the materials and on the isolators, need to be available at the beginning of the process and adapted to the quantities and the manufacturing steps. These controls typically cover a dedicated process or procedure. For example, monitoring of a test to qualify a process or a material healthiness (e.g. mechanical test on rubber to check the vulcanization), or measuring the mechanical properties of the final product (e.g. full-scale mechanical tests on isolator performed on 2D or 3D hydraulic press).
- The deviations of the main mechanical properties are based upon initial test results performed on prototypes as compared to target values. The deviations need to be low but industrially achievable (e.g. ±10% for main properties of rubber bearings, measured on full scale isolators). The tests are typically both, static and dynamic, at full scale, and at a reduced scale, if relevant. The percentage of tested specimen needs to be justified according to safety criteria (e.g. 1-2% of total number of units produced and tested through dynamic shear tests for the last French projects). For sliding bearings, the characteristics of polytetrafluorethylene (PTFE) needs to be controlled for each batch.

7.3. TECHNICAL REQUIREMENTS FOR CONSTRUCTION STAGE

To extend the delineation of the safety functions of the isolation system to the construction and in-service period, the quality control of the seismic isolation needs to be conducted based on an appropriate quality management plan. The overall isolation system is to be treated as a structural subsystem.

The interface between the superstructure and substructure is to be addressed. Attention should be paid to the following non-limitative points:

- Tolerances and geometry of the substructure (such as pedestals) need to be compatible with the shear load transmission (e.g. concrete reinforcement is to be compatible with the connectors, and embedded plates are to be equipped with studs to distribute the horizontal force to the substructure).
- The erection sequence (pouring method including shoring and propelling removal) is to be compatible with isolator settlement and rotation.
- Settlement and adjustment procedures for the installation of isolators are to be compliant with the design assumptions (such as flatness tolerances, force distribution variation, etc.).
- Grouting and final installation of the isolators need to be carefully executed (to prevent voids under embedded plates, allow for flatness adjustments, etc).

These issues need not be considered as secondary issues since a lack of quality and control of this final step can jeopardize the effort and concerns invested during manufacturing.

7.4. TECHNICAL REQUIREMENTS FOR OPERATION STAGE

Isolators have to maintain the required safety functions over the service period of the plant. Thus, base isolated SSCs have to undergo regular inspections and testing. A specific surveillance program is to be established.

Regular periodic inspections of the isolation system need to be performed, in addition to mechanical tests on representative isolators – this will indicate the evolution of the mechanical properties versus ageing.

In case of earthquake (or other extraordinary event), seismic response of the base isolated structure needs to be monitored (in a sufficient manner to understand the behaviour of the system, including torsional and rocking motions). In order to confirm the performance of isolated structures, the following items need to be checked:

- Damage to the superstructures, the substructures, and the isolation devices,
- Positions of superstructures after the event,
- Presence of damage in isolation devices.

On soft soil sites, settlement needs to be monitored, throughout the complete service life of the plant, and its effects on vertical loads and behaviour of the isolation system need to be assessed. The aim is to determine the possible redistribution of loads on the bearings and address discrepancies between design and actual loads supported by the devices. Settlement effects on vertical displacements at the top of the pedestals, supporting pedestals, and lower raft need to also be monitored. Creep effects and differential displacements of devices need to also be monitored and addressed.

In any case, damaged isolation devices which cannot fulfil their isolation functions need to be replaced. The design of the isolation system and the feasibility of replacement of isolators is to be addressed at the beginning of the design stage.

8. ECONOMIC CONSIDERATIONS

The main motivations for use of isolation systems for nuclear installations are:

- Progressive, steady, and essential increase of nuclear installation sites' seismic demand. In the last decade the DBE for some installations has reached a range of 0.4 to 1.0g PGA with BDB seismic events greater than 1.5g on some sites;
- Steady increase of nuclear installations' seismic design and construction costs and vendors' costs for supplying SSCs with high seismic capacity.

Seismic isolation provides to the nuclear installation:

- Increase of NI safety under seismic and other dynamic loads.
- Lower accelerations on structures, systems, components, equipment, and piping.
- Lower weight and cost of internal structures, components, equipment, piping, and supports.
- Possibility for a conventional or minimal standard seismic design of SSCs.
- Simpler structural behaviour resulting in simpler structural analysis.
- Greater flexibility in overall design of buildings: less stringent slenderness conditions, possibility of locating heavy equipment on upper floors, etc.
- Decrease in uncertainties in PSA analysis (one key system provides seismic safety).
- Decrease in public pressure. Seismic isolation systems allow mitigating concerns over NPPs seismic vulnerability in the eyes of the public, mass media, and authorities.

Some of the limitations of seismic isolation applications are:

- Extended relative seismic displacements of internal and external structures require extended flexibility of distribution systems (umbilical problem).
- Demand on extreme reliability of SIS as the key system responsible for NPP's seismic safety and structural behaviour.
- Need for a specific definition of BDB event margin for SIS.
- More complex design and cost of slotted foundation separated into a substructure and a superstructure.

The effect of applying a seismic isolation system needs to be comprehensively evaluated considering safety and economic efficiency and feasibility.

For the design phase, the following points need to be considered: cost of isolation devices, cost of infrastructure, and consequences of longer construction schedule. In turn, the use of an isolation system will increase the global seismic safety, allow use of standard equipment (pre-qualified), simpler supports, less reinforcement, etc. All these elements can lead to a decrease in overall cost.

The total cost of the seismic isolation system during the in-service period is typically estimated considering the initial costs and expected failure costs. The expected failure costs include direct costs related to the seismic isolation system, and indirect costs related to independent variables such as loss of power.

At this time, such cost analyses, for a nuclear power plant, have not been published. An exercise has been performed for seismic isolation of an emergency diesel generator [50], which found that the system is cost effective in terms of total expected failure costs and leads to an improvement of seismic safety. When indirect failure costs, such as forced outages after an earthquake (see for instance Kashiwazaki-Kariwa case after the 2007 Niigataken Chuetsu-Oki earthquake), are included in the cost analysis, base isolation becomes significantly more competitive.

9. INDEPENDENT REVIEW

A specific independent (peer) review program dedicated to the seismic isolation process needs to be implemented to review the design of the isolation system, the related test programs, and the design of the isolated structures. Typically, the peer review, at a minimum, covers the following items (as applicable for the phase of review):

- Isolators design: materials, dimensions, etc.
- The general layout of the facility, in relation to seismic isolation: lower raft, pedestals and moat, and associated construction tolerance specifications.
- Soil data and characteristics considered in analyses.
- Adequacy of site seismic input, specifically for low frequency content.
- Numerical models of isolators.
- Bearing design criteria (distortion, compression, tension, buckling, etc).
- SSI analysis and the resulting in-structure response spectra.
- Displacement and force calculations for the isolator units and all associated structures, systems, and components.
- Analysis and design of the umbilicals.
- Analysis of the gap or analysis and design of the hard stop.

- The prototype test program.
- Production (quality control) test program.
- Isolator replacement and adjustment procedures.
- Isolator inspection and post-installation testing program.
- Post-earthquake inspection protocols.
- Design for other external events (behaviour of isolation system).
- Protection measures of isolation system against other external events.
- Beyond design considerations.

The independent peer review is to be conducted by experts in the listed areas, specifically experienced in seismic isolation design, large scale testing of components (such as isolators), and in ageing of materials (if necessary) according to the type of isolators.

APPENDIX – BASIC ELEMENTS OF ISOLATION DEVICES

A.1 Bearing devices

Elastic type elements such as rubber bearings, mechanical elements such as sliding bearings, and springs, can be used as seismic isolation devices. They will be described in this Appendix. The cyclic (and dynamic) mechanical properties of some of them may be complicated with non-linear behaviour, interaction between different loading directions, and possible ageing coupling. The USNRC document [11] requires devices to be “analysable”. In all cases, test campaigns (including full scale tests) have to be performed as presented in Section 7.

A.1.1 Laminated rubber seismic isolation elements:

The technique used for manufacturing of laminated rubber seismic isolation elements resulted from early 1950s improvements of rubber bearings. The improvements were achieved through interposing steel plates between rubber layers in order to increase the vertical stiffness of the isolation devices. The mechanical properties of rubber are characterized by a very important deformation at rupture, and a large elastic zone. Elasticity is achieved by vulcanization (or curing or cooking) of rubber (with addition of a sulphur or equivalent). Using additives during the process may modify the duration of the process itself and/or the material’s mechanical properties such as resistance, yield limit, stiffness, damping characteristics, etc.

The bearing is a succession of layers of rubber and steel plates [16]. The steel plates limit the stress in the rubber under vertical loads and increase the vertical stiffness necessary for the supporting function of the bearing. The typical thickness of the rubber layers is about 10mm and of the steel plates - greater than 2mm. Bearings are either circular or square, with very comparable distortion behaviour. Typical maximum horizontal size dimensions are less than 2m (metric size is usual). The dimensions are limited by the need for homogeneous vulcanization. The bearings support the vertical loads (weight plus variable loads plus vertical loads due to earthquake – vertical and overturning), the horizontal seismic loads, and the applied raft deformation (creep, temperature, etc.). The progressive development of manufacturing, design, and control of the isolation bearings in the mid-1970s lead to the possibility of nuclear installation applications. The mechanical behaviour is essentially governed by the horizontal stiffness, K_h, which is given by the simple formula:

$$K_h = \frac{G_d \, .A_s}{h} \tag{1}$$

Where,

G_d is the dynamic shear modulus of the rubber, under seismic conditions

A_s the section of rubber (part contained in the steel plates)

h is the total thickness of all rubber layers.

In high damping rubber bearings, the shear modulus is strain dependant and is sensitive to the velocity of the applied load and the number of applied cycles. Therefore, the vertical stiffness is some order of magnitudes higher and its determination is less straightforward than that of the horizontal stiffness. Some formulas are proposed in textbooks and standards, but there is no consensus about them. They include the primary shape factor which is the ratio of free of load surface (lateral surface) and the loaded surface of a rubber layer. For nuclear applications, full scale vertical tests are necessary and required by most standards [51].

To prevent potential failure modes of rubber bearings the following points are usually checked:

- The **maximum horizontal shear distortion** under seismic loads.
- The total **maximum shear strain** in the rubber layers under vertical and horizontal loads, including distortions due to creep and shrinkage of concrete. Strain due to angular distortion is limited, with an imposed minimum thickness of steel plates. This condition may control on site tolerances for bearing installation.
- **Buckling** of bearings under combined vertical and horizontal loads - can be prevented by verification of the slenderness with appropriate formulations.
- **Mean compressive** stress under the bearings is usually limited (typically to 6-8MPa) under permanent loads.
- **Tension** in isolators essentially due to uplift caused by overturning or strong vertical component in high seismic region. The occurrence of tension requires to fix the bearings to the pedestal and the superstructure upper raft.
- **Roll-over** is a global instability due to excessive horizontal load (only if the device is not fixed to the pedestal and upper raft) and is to be considered in margin assessment and beyond design considerations.

For all the failure modes, formulations are included in design codes. Reference [16] presents an explanation of physical phenomena and their quantification.

There are basically three types of elastomer bearings described below.

A. Low damping rubber bearings (LDRB)

The most basic elastomer bearing is shown in Figure A.1 (with either natural or synthetic rubber). The most common synthetic rubber is polychloroprene, often called Neoprene (Trademark). Different additives are included either in synthetic or natural rubber in order to improve their characteristics. The USNRC text [11] addresses only natural rubber, and only acknowledges synthetic rubber; this means that this material is not prohibited but not covered. The French practice is based essentially on synthetic rubber. Each of these materials has advantages and disadvantages. For both, ageing modifies the mechanical properties, mainly increasing the shear modulus. Damping is less affected by ageing. Synthetic rubber is less sensitive to ozone attack and it is more resistant to fire, being self-extinguishable. Natural rubber is usually (depending on the compound) more resistant to very low temperatures and has a higher elongation capacity.

Typical force-distortion behaviour (shown Figure 4.2 of reference [11]) shows that at 75% distortion the behaviour is essentially linear while at a peak shear strain of 175% the behaviour becomes more nonlinear. In these bearings typical maximum strain can be around 300% or more. The dynamic shear modulus depends on the rubber material and is typically between 0.5 to 1.2MPa; the European code [13] mentions values between 0.3 and 1.5MPa at 100% distortion. Allowable distortion under seismic loading is one of the main dimensioning conditions; European codes for conventional structures give a value of 250% (see Ref. [13]). In French nuclear practice, for devices with an important industrial role, the allowable strain under seismic design loads is 140% (see [17]). In Japanese and USNRC practices, the allowable value needs to be determined from a testing programme. In Japan, the general principle is to determine the linearity limit (see Annex IV) of the bearing and add a margin of 1.5. There is no detailed guidance on how the linearity limit is defined. Typical distortion values used in Japan for design are 200 or 250%. Some ultimate tests for LDRB result in ultimate behaviour at distortion up to 500%.

Compressive resistance of bearings is important (>20MPa); for design, a compressive stress of about 7-10MPa is considered in EN 15129 [13]; this is used to determine the number of bearings under the plant. Vertical stiffness is driven by the thickness of rubber layers and is generally more important than horizontal stiffness.

When stressed in tension, some cracks may appear at stresses around 1.5-2MPa; this value depends on the rubber compounds. This phenomenon is called cavitation. In the European code [13], the allowable tensile stress is 2Gd. Some rubber can be stressed at significantly higher values with significant elongation. Typically, codes require no-tension on rubber bearings in seismic conditions, and some - a required residual compressive stress (about 1MPa). There are codes that do not explicitly exclude tension under extreme loads. Bearing may, but do not necessarily need to be anchored, to sub- and superstructure; therefore, requirements on allowable tension may vary.

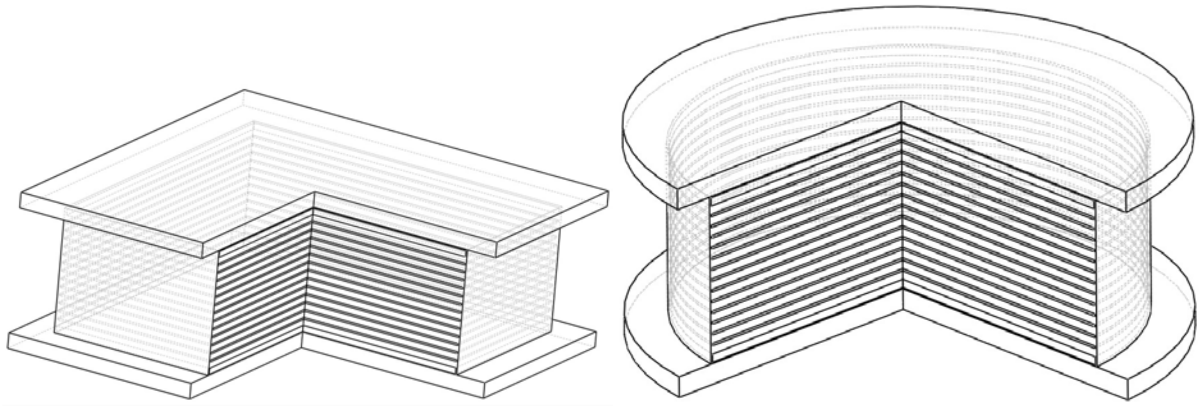


FIG. A.1 Rubber Bearing (RB) courtesy of NUVIA

One important characteristic of rubber bearings is the variation of properties due to different causes:

Variations from one bearing to another include:

a. properties
b. constituents of the rubber mixing
c. characteristics of the vulcanization process.

QA processes and procedures at the time of manufacturing can significantly decrease these variations.

Temperature has an important effect on mechanical properties. At very low temperature (about -40°C for natural rubber and -15°C for synthetic, both cases depending on the compound), rubber loses its elasticity. For nuclear applications however, the isolation system is very often naturally protected (due to embedment in the soil and presence of massive concrete volume surrounding the nuclear island - it is noted that this may not be the case for a separately isolated SSC, such as a diesel generator), temperature variations are limited, shear modulus and damping vary very slightly (about 10% for shear modulus).

Mechanical properties of rubber, natural or synthetic, vary with time due to ageing phenomena, related to the continuation of the complex vulcanization process. As consequence, there is an increase of shear modulus and a reduced variation in damping. Oxygen and ozone are the main ageing agents, which have more effect near the surface; antioxidant and anti-ozone treatment near the outer surfaces reduce this phenomenon. Effect of ageing on mechanical properties can be anticipated by accelerated aging tests which are normalized in European codes, for instance. For a lifetime of 60 years, the increase of shear modulus due to ageing is about 1.2 to 1.4. With the NR compounds used in the USA, accelerated tests are not used and increases in shear modulus are lower. In Japan, the increase of shear modulus is considered to be about 10%.

The effect of cyclic loads shows that, for example, the shear modulus properties are higher during the initial cycle and decrease with the number of cycles. This phenomenon is called scragging of rubber. Damping values may also decrease as the number of cycle increases. This effect is related to a modification of the structure of the polymer. For low damping rubber, the effect is usually limited.

B. Lead rubber bearings (LRB)

In order to increase the damping of a rubber bearing, or decrease the overall distortion of the bearings, a lead plug can be inserted in one (or several) central holes of a LDRB - as shown in Figure A.2. Typically for circular isolators, the diameter of the core is about 1/4 to 1/3 of the bonded diameter of the bearing.

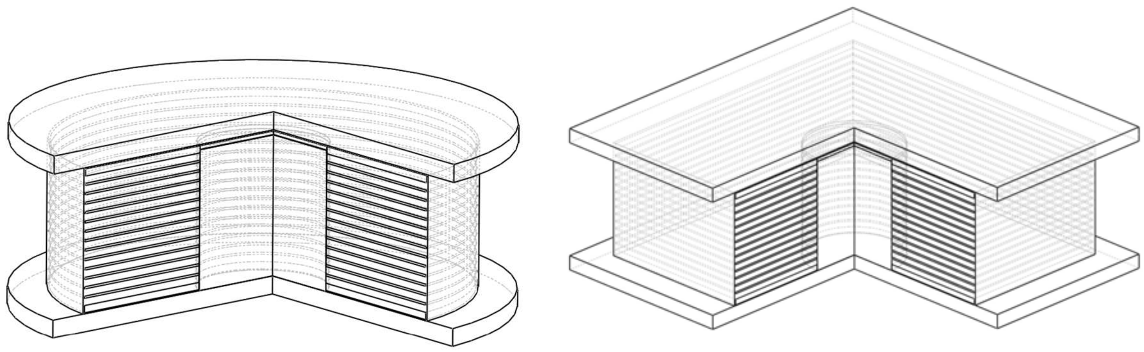


FIG. A.2 Lead Rubber Bearing (LRB) courtesy of NUVIA

Lead has the specificity to be very rigid at low strain and perfectly plastic above yield. In addition, it recovers its initial mechanical properties after deformation (it is a malleable material). The presence of lead increases the damping by a hysteretic effect. After vulcanisation of the bearing, the lead core is inserted in the hole(s) of the bearing, such that the interaction of the lead and rubber is optimized.

Figure A.3 shows an idealized force-displacement curve of an LRB, where Q_d represents the yield force of the lead core and the hardening slope includes the rubber and the lead rigidities. The ultimate behaviour of an LRB is influenced by the lead core geometry.

The evaluation of damping can be made by linearization of the hysteretic curve as in Figure A.3; damping is characterized by the area inside the curve divided by the potential energy stored in the equivalent spring at the maximum displacement; this gives values up to 30-35%, according to the geometry of the lead core.

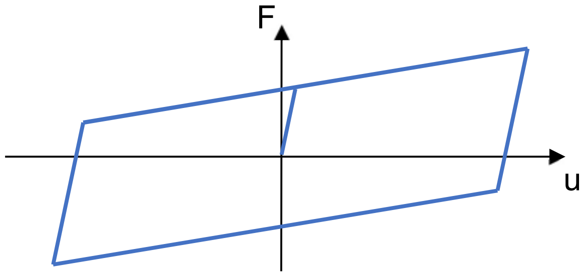


FIG. A.3 LRB – Idealised lateral force displacement behaviour

The vertical compression rigidity depends on the size of the lead core and on the overall bearing slenderness. However, with horizontal distortion, the overall vertical behaviour is not so simple, because the effect of -confined or not- lead is not clear, and certainly deserves attention [52]. The estimation of buckling conditions needs to take into account the presence of the lead core. In tension, the lead core does not play a significant role.

The variation of properties of the rubber part are those explained in part B, above. A specific situation arises from the behaviour of lead. Under cyclic loads the lead, subjected to alternating strains will heat up. Since it is confined, the temperature can increase significantly. As a result, the damping and yield stress of the lead core will decrease. The mechanical properties of lead are not expected to vary with time. Ageing characteristics of LRB are as described in part A.

C. High damping rubber bearing (HDRB)

Adding products (additives) to natural or synthetic rubber allows for a change of mechanical properties and, in particular, increase of the rubber's internal damping up to 10%-15% (even 20% by adding oil) [53]. Figure A.4 shows hysteretic loops for a 110% distortion and 220% distortion of HDRB. The first curve is rather regular, with important damping. The second curve shows that at higher strains; the slope increases, which is typical of these materials. The increase in stiffness may be considered as a protection for beyond design situations, and/or as a fail-safe system, by limiting the displacement.

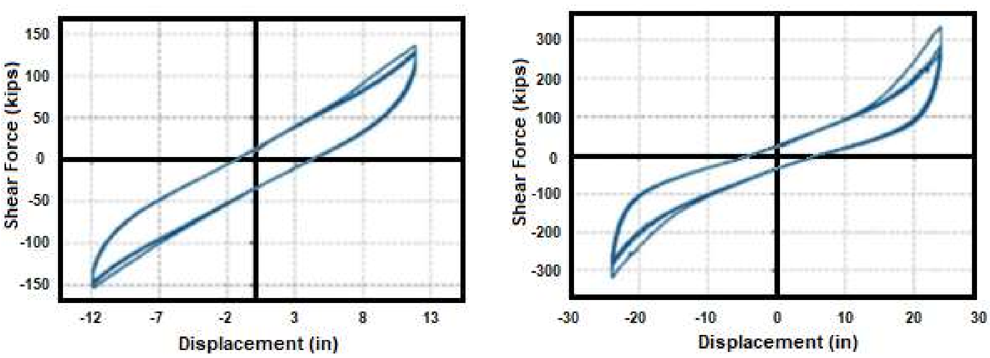


FIG. A.4 Hysteretic loop of HDRB (at 110% - left and 220% - right)

General properties of HDRB are globally comparable to LDRB, concerning shear, tension and compression behaviour. However, HDRB are subject to significant scragging, depending on the compound, with characteristics varying with the applied cycles. It is considered, for instance by the USNRC [11] document, that due to this phenomenon and unpredictable changes in properties over time, these bearings are not suitable for use in NPPs. Due to these variations and changes these bearings may not be modellable before manufacturing and/or installation on site. Scragging is shown in Figure A.5 from reference [53], where the blue curves correspond to the first cycle and the orange to the tenth cycle. Scragging characteristics depend mainly on the properties of the additives used to increase the damping.

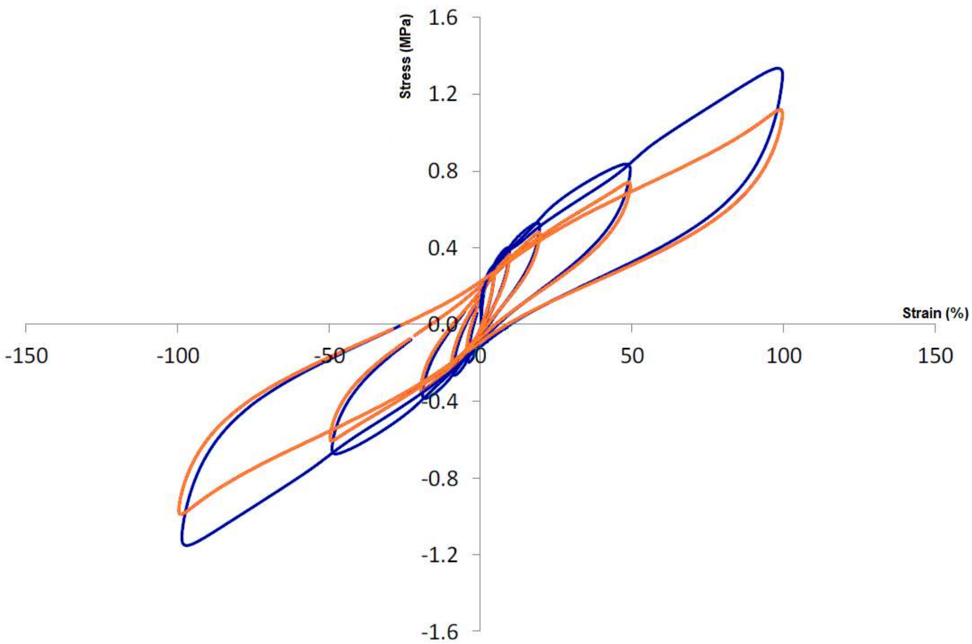


FIG. A.5 Cyclic horizontal behaviour of HDRB

HDRB have been used in isolation of conventional buildings in the USA and in the UK, in the latter case for transport induced vibrations protection, and in the former for seismic isolation. Therefore, some feedback of actual experience with HDRB ageing may be obtained from these examples.

A.1.2 Sliding devices

A. Rigid sliding bearing

The theoretically most simple device is a sliding pad on a fixed plate. This type of bearing is typically used for coping with thermal expansion in bridges. The behaviour of such a system follows a rigid- plastic law with no sliding if the horizontal force is lower than μ*V, where μ is the friction coefficient and V the vertical compression force. If the lateral force is higher, there is sliding. In this system the acceleration on the sliding part is limited to μg, and consequently filtered. The reality is less simple for different reasons: the friction coefficient is often not unique, the force necessary to start sliding being higher than the force to have permanent sliding (static and dynamic coefficients). Furthermore, if the vertical load is not constant, as in the case of overturning due to earthquake, the dynamics are more complicated. The floor response spectrum of the acceleration above the pad may be rich in high frequencies due to the intermittence of slide and stop associated with the variability of the friction coefficient. The effect on equipment is then not so positive.

An essential aspect is the choice of materials for the plate and for the sliding part. The most common materials are stainless steel for the plate and polytetrafluorethylene (PTFE) (aka Teflon © as a Du Pont trade name) for the sliding part. PTFE is used for more than 70 years, it has an excellent corrosion resistance. On steel, it is possible that some wear occurs, but it is for extremely long distances of friction, having nothing common with seismic displacements. The friction coefficient depends on temperature (the friction coefficient decreases as temperature increases) and on the applied vertical load (as load increases the friction coefficient decreases). These properties can be simulated in analysis models. During the earthquake, as a result of friction, the temperature may increase significantly. If seismic axial loads are high, uplift may occur, which complicates the behaviour of the bearing.

In Koeberg, RSA, a system with sliding plates placed above a LDRB was installed to isolate two 900MWe units constructed by the French. The slider consisted of two plates, an upper (stainless steel), and a lower (lead-bronze alloy fixed on top of the LDRB). This was a unique application of a bimetallic surface combination, which is not recommended by the USNRC document [11]. One main concern with this methodology is the long-term behaviour of the surfaces, which may be difficult to demonstrate.

To address the non-linear, non-centring behaviour of rigid sliding bearings an elastic device can be added to the sliding pad. Typically, a laminated rubber bearing can be used. It is noted that the main characteristics of rigid sliding bearings are applicable to the elastic device and are to be accounted for in analysis and design.

B. Curved surface sliders

A general definition is provided in EN 15129 [13]: Curved surface sliders are seismic isolators that provide the four main functions through an appropriate arrangement of curved sliding surfaces and use the characteristics of a pendulum to lengthen the natural period of the isolated structure. The curved main sliding surface of Curved Surfaces Sliders provides a restoring force at displacement. Energy is dissipated by friction due to movement in the main sliding surface. Rotations of the structure are accommodated by the secondary sliding surface [54].

A significant improvement of sliding bearings is obtained by replacing the steel plane plate by a concave spherical one, as shown in Figure A.6, which presents one possible case. Another configuration, where the steel bowl is at the base, for instance, is possible. The slider is, in the figure, articulated at its lower part allowing a full contact of its upper sliding part with the steel spherical bowl. Materials used in these devices are similar to the plane sliding bearings.

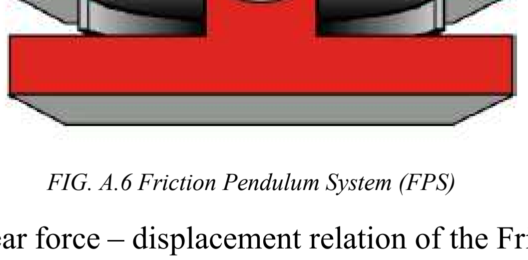


FIG. A.6 Friction Pendulum System (FPS)

Figure A.7 shows the shear force – displacement relation of the Friction Pendulum System.

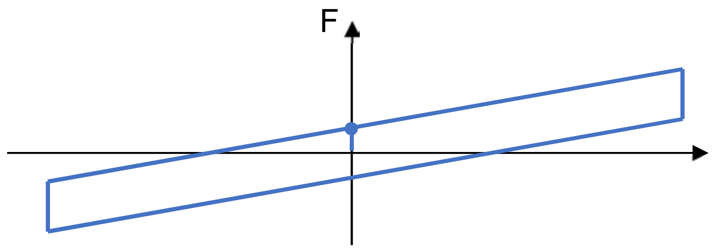


FIG. A.7 Shear force-displacement relation for an FPS

Two parameters, μ (friction coefficient) and R (radius of curvature), characterize the behaviour of the isolator. Under compressive load, the bearing is rigid; in tension, there is no “rigidity” and tension needs to be avoided by design.

As a consequence of the restoring force equation, the frequency of oscillation of a mass fixed to the top plate is independent of the value of mass (pendulum behaviour). This behaviour is only observed if the isolated structure is “flat” and does not have an overturning moment due to the horizontal earthquake component. The variation of loads due to overturning will influence the response frequency; this effect is always considered in analysis.

As for flat plates, the friction coefficient decreases with increasing stress and temperature. The main points to be considered are wear of the sliding surface, temperature increase during cycling and ageing of the sliding material. The allowable relative displacement between the lower and upper plates is limited by construction; the allowable value is typically considered for design and beyond design cases. Due to the curvature, there is a kinematic coupling between horizontal and vertical movements, which are to be taken into account in the analyses. In most cases, the lower and upper plates are fixed (anchored) to the pedestal and upper raft.

There are many applications of the system in conventional buildings and in high hazard facilities, such as LNG tanks, with quality requirements approaching the nuclear industry ones.

A.1.3 Springs

Spring elements are the simplest rigidity elements. In order to maintain bearing capacity, it is recommended to couple springs in parallel as shown in Figure A.8. Spring elements with helical steel springs possess linear-elastic behaviour in both horizontal and vertical directions. However, as soon as some horizontal movement occurs, there is a coupling between the horizontal and the vertical movement. The horizontal stiffness is equal for both horizontal directions. Therefore, their numerical description is relatively simple and the behaviour of the structure on these devices can easily be assessed. The elements carry the dead load of the structure and are designed to have sufficient safety margin to also bear additional loads (in both horizontal and vertical directions) from seismic excitation. There is no difference between the static and dynamic characteristics of the steel springs. Such types of devices are used mainly for vibration isolation of sensitive equipment or turbines. They are used for seismic isolation applications as well.

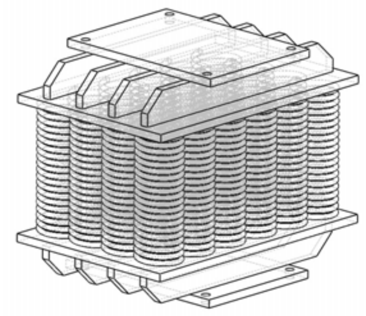


FIG. A.8 Typical spring element and example of measured parameter

For vertical supporting systems, pneumatic springs have been proposed as part of a 3D seismic isolation system for advanced nuclear power plants [47].

A.1.4 Other

There are many devices developed mainly for equipment seismic isolation. Some of them are listed below:

- Plane roller bearings, where cylindrical rollers are placed between two steel plates, allowing their virtually free movement in the direction perpendicular to the cylinder axis.
- Rail rollers with low friction linear bearings assembled by pairs and possibly in two directions.

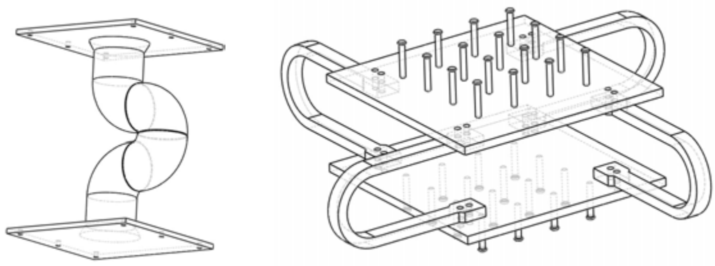
These devices are readily available and can be directly applied to equipment. They don't need to have a long design life since, they can be replaced easily. Quite often equipment which is isolated with these types of isolation elements will be replaced during the life of the installation. However, each device typically has a qualification report, with a description of the characteristics of the device and of its maintenance programme.

A.2 Dampers

In order to control the distortion of bearing devices, it is possible to add damping elements. There are two categories of dampers:

A.2.1 Elastic-plastic hysteretic damper

Energy dissipation is obtained by deforming a stainless steel, lead, or other type of mechanical element elasto-plastically. The mechanical elements have an adapted shape in order to accommodate all large plastic deformations without strain concentrations. Mechanical dampers have many shortcomings, such as creep (for lead), behaviour during aftershocks, effects on vertical response, etc. The dampers need to be inspected and replaced often during the life of the facility. They can also be used for isolation of equipment. Figure A.9 shows two examples (a lead and a steel damper):



Lead damper Steel damper

FIG. A.9 Examples of Dampers courtesy of NUVIA

A.2.2 Viscous dampers

These devices use the viscosity of a fluid, such as oil, by creating either a movement of oil between cavities (controlled by a valve), or by moving a plate or a piston through a viscous liquid. The associated force is generally of the form:

$$F = C \times V^{a} \qquad (2)$$

Where a depends on the device. V is the velocity. C is a coefficient dependant on temperature and on frequency of the movement. They can act in one direction (1D) or in the 3 directions (3D) (see Figure A.10(A) and A.10(B)).

Some of these systems require maintenance and need to be accessible and replaceable.

FIG. A.10(A) 3D Dampers

FIG. A.10(B) 1D Dampers

Figure A.11 presents a system which can be mounted in parallel to other types of bearings: LDRB or springs. For example, dampers and isolators can be mounted in parallel in order to provide prescribed force and damping values, as reported on Figure A.11.

FIG. A.11 Isolators and dampers mounted in parallel

A.3 Three-dimensional isolation

There was a tendency to design devices which allow three-dimensional seismic isolation of a complete structure. The seismically isolated story is located at the base of the structure and results in vertical flexibility, which means the structure has a low vertical frequency (typically 0.6 to 2Hz) that induces rocking. For equipment or small structures, rocking may be acceptable. However, for large structures, such as buildings of a nuclear power plant, it may induce complex horizontal behaviour. Reference [47] proposes an example of an anti-rocking device for an isolation project of advanced reactors. The presented isolation approach uses a vertical cylindrical pneumatic system for vertical isolation and rubber bearings for the horizontal, located on the bottom or the top of the vertical support. In order to avoid rocking, the extreme vertical supports are linked through air pipes which assure equally distributed pressure amongst the supports which suppress rocking (see reference [55]).

The proposed 3-dimensional isolation solution complicates the overall system, with the introduction of safety-related air piping within the substructure, which would require precise tuning and monitoring. However, the referenced paper shows that such systems are plausible and may be feasible for future projects [48]. At this time there is no examples of applications of such systems in high hazard industrial facilities.

Coil springs and 3D viscous dampers can also provide 3D isolation. Such a system would allow tuning of the horizontal and vertical stiffnesses separately to optimal parameters. Additionally, installation of 3D viscous dampers separately, can ensure limited displacements and minimal rocking effects [56].

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ANNEX I BASE ISOLATED NUCLEAR PROJECTS

TABLE I-1. BASE ISOLATED NUCLEAR FACILITIES

Facility	Country	Type	Year	SI description
EFR ESFR	Europe	FBR	80s	Horizontally Isolated Building with LDR Vertical isolation of main Vessel, Springs and dampers
PRISM	USA	Small WR	Mid 80s	20 HDRBs
SAFR	USA	Fast Reactor	Mid 80s	
KALIMER	Korea	Fast Reactor		
ALMR	USA	Fast Reactor		
STAR-LM	USA	LMR Gen IV		3D H: RB V: Springs
IRIS	Internati onal		2000s	Horizontal isolation with 99 HDRDs
SILER	Europe	GEN IV reactors	2012	
ASTRID	Europe/ France	GEN-IV SFR	Under development	Horizontal low damping Neoprene isolators
ALFRED	Europe/ Romania	GEN IV LCFR	Under development	HDRB

ANNEX II BASE ISOLATED EMERGENCY BUILDINGS CONSTRUCTED IN JAPAN NUCLEAR POWER PLANTS

New Administration Building built in 2011 with layout as shown in Figure II-1:

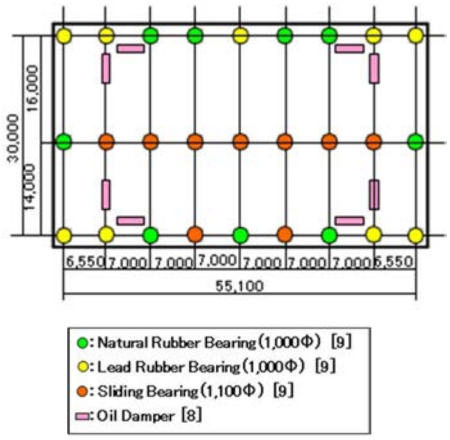


FIG. II-1. Layout of Seismically Isolated Administration Building

Emergency Response Building built in 2009 with layout as shown in Figure II-2:

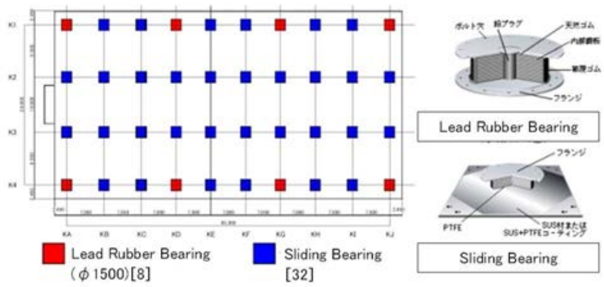


FIG. II-2. Layout of Seismically Isolated Emergency Building

Emergency Response Building built in 2010 with layout as shown in Figure II-3:

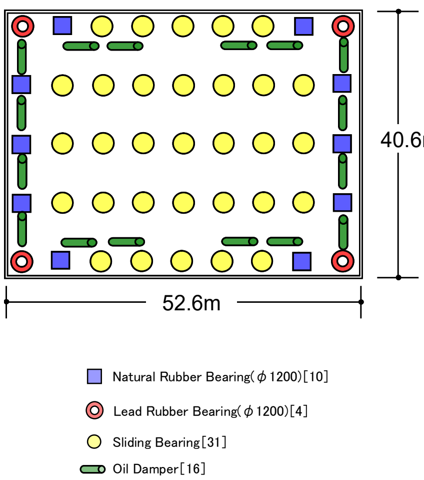


FIG. II-3. Layout of Seismically Isolated Emergency Building

Emergency Response Building built in 2010 with layout as shown in Figure II-4:

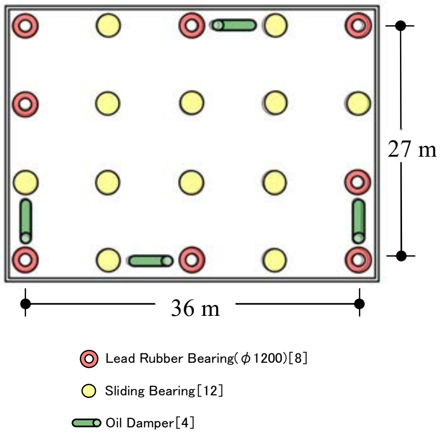


FIG. II-4. Layout of Seismically Isolated Emergency Building

Emergency Response Building built in 2010 with layout as shown in Figure II-5:

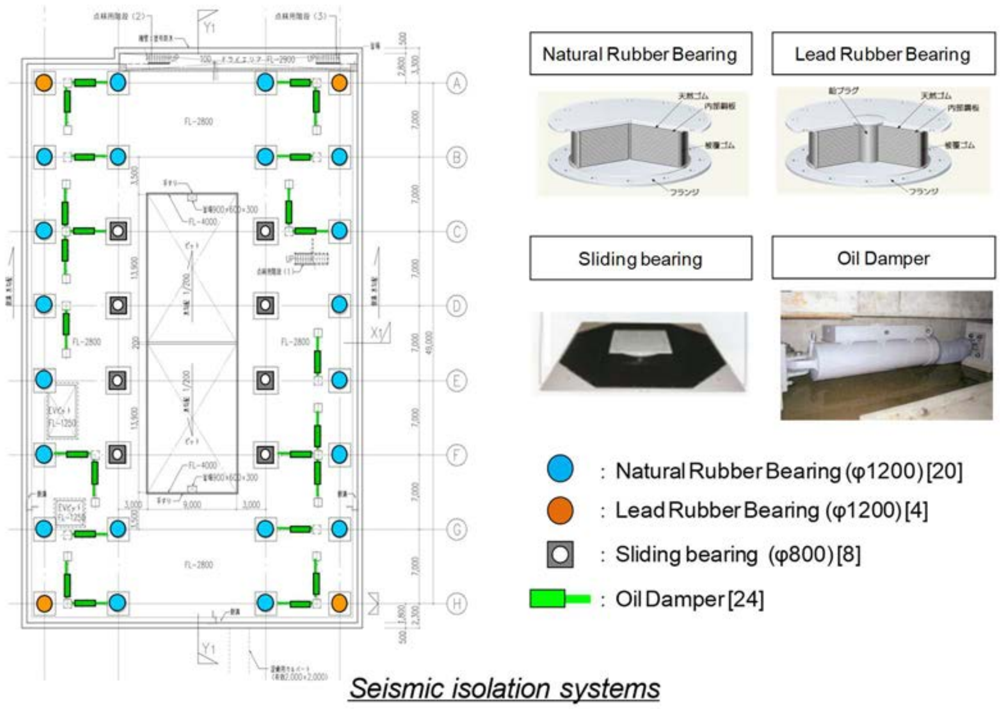
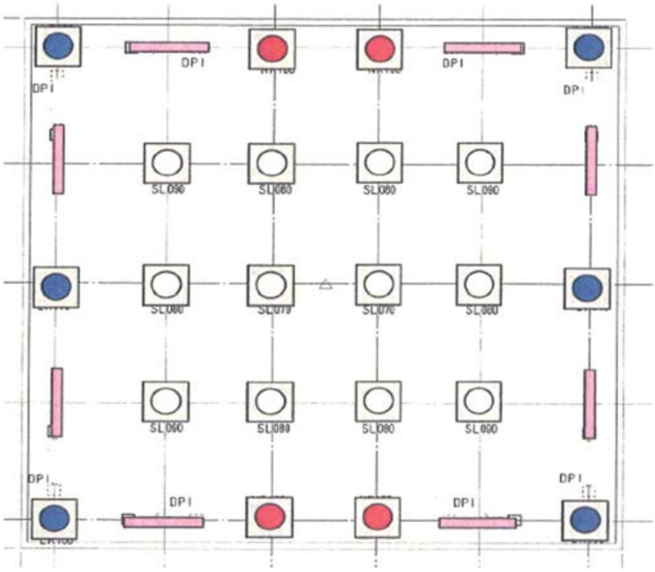


FIG. II-5. Layout of Seismically Isolated Emergency Building

Emergency Response Building built in 2013 with layout as shown in Figure II-6:



: Natural Rubber Bearing (φ1000) [4]

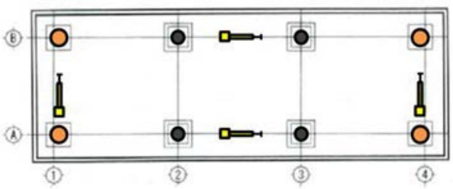
: Lead Rubber Bearing (φ1000, φ1100) [6]

: Sliding bearing (φ700, φ800, φ900) [12]

: Oil Damper [8]

FIG. II-6. Layout of Seismically Isolated Emergency Building

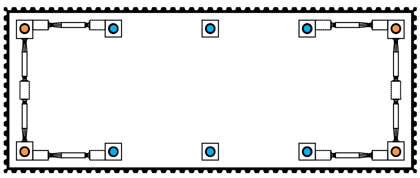
Emergency Response Building built in 2010 with layout as shown in Figure II-7:



:Lead Rubber Bearing(ϕ1200) [4]
:Sliding Bearing(ϕ800) [4]
:Oil Damper [4]

FIG. II-7. Layout of Seismically Isolated Emergency Building

Emergency Response Building built in 2011 with layout as shown in Figure II-8:



:Natural Rubber Bearing(ϕ800) [6]
:Lead Rubber Bearing(ϕ800) [4]
:Oil Damper [8]

FIG. II-8. Layout of Seismically Isolated Emergency Building

New Administration Building built in 2011 with layout as shown in Figure II-9:

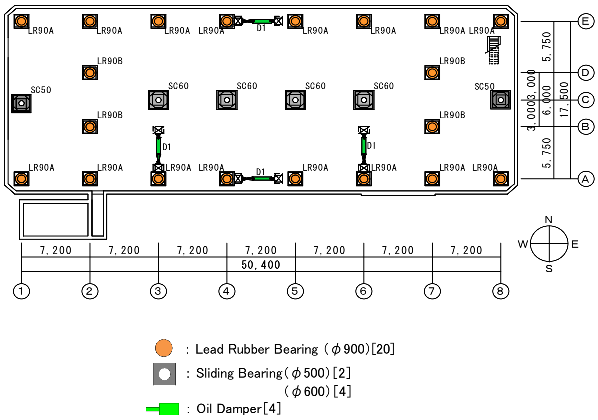


FIG. II-9. Layout of Seismically Isolated Administration Building

Emergency Headquarter Building built in 2011 with layout as shown in Figure II-10:

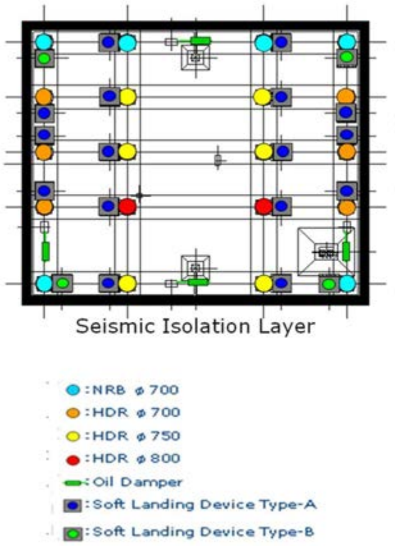


FIG. II-10. Layout of Seismically Isolated Emergency Building

ANNEX III PERFORMANCE OF SEISMICALLY ISOLATED STRUCTURES TO SEISMIC EVENTS

TABLE III-1. PERFORMANCE OF SEISMICALLY ISOLATED STRUCTURES

Structure description	**Isolation system*****	**Year of construction**	**Acceleration H, V / Distortion**	**Behaviour during earthquake**
Northridge earthquake ML 6.7				
USC Hospital Steel structure, unsymmetrical, 7- levels Basemat dimensions: 92mX77m 49km from epicentre	81 (almost) square LDRB (natural rubber) and 68 LRB, circular. Lead Diameter 14cm Total height: 34.6cm		Horizontal Free field 0.49g Foundation 0.37g Basemat 0.13g NS 0.14g EW Top 0.21g NS 0.19g EW Max distortion of isolators: 3.5cm (13% of design value)	No structural damage Due to asymmetric plan, torsion is present in the response. Filtering by BI is effective.
Landers Earthquake MS 7.5				
Foothill Communities Law and Justice Centre; 4 levels steel structure with X bracing in longitudinal and V in lateral directions. Plan shape is rectangular (34mX126m). First seismically base isolated building in California 106km from epicentre	98 circular HDRB; Diameter 76cm, total height 46cm, Rubber 30.5cm		Ground: 0.11g Base: 0.09g Top: 0.19g Distortion: 1cm (3% of total rubber thickness)	The acceleration at the site was limited and so was the distortion of isolators. Shear modulus of high damping rubber is very sensitive to distortion. At the limited distortion, the frequency of the isolated structure was higher than for the design value. It explains the amplification of roof acceleration in comparison to that of the basemat. For nonlinear isolators, different levels of excitation are typically applied in analysis and design, specifically to define in-structure floor response spectra.

Structure description	Isolation system***	Year of construction	Acceleration H, V / Distortion	Behaviour during earthquake
Hyogo-ken Nanbu (Kobe) earthquake of January 17, 1995; M = 7.3				
Computer Centre of Ministry of Post and Telecommunications 6 levels building, 80x80m in plan; RC frame structure, steel bracing About 50km from the epicentre	56 LR bearings, diameter 1.2m, Rubber thickness: 24cm 46 Natural Rubber bearings; diameter 1m, Rubber thickness: 20cm 20 Natural Rubber bearings; diameter 0.8m, Rubber thickness: 16cm 44 steel dampers		Ground: 0.3g-0.2g Base: 0.11g – 0.19g Top: 0.10g - 0.38g Distortion: 17.6cm, Max allowable distortion: 40cm	No specific question.
West Building, Kobe, Hyogo, Japan Structural frame: Six-storied composite rigid frame building with steel braces. Structural plan: 82.8m x 110.2m Distance from the epicentre: 30km * Located close to the next building	Natural Rubber Bearing (□ 800/1000) [66 units]; Lead Rubber Bearing (□ 1200) [54 units]; and Steel Damper [77 units]	1994	Base: 0.263G (H1), 0.300G (H2) and 0.213G (V) 1FL: 0.057G (H1), 0.106G (H2) and 0.193G (V) 6FL: 0.075G (H1), 0.103G (H2) and 0.377G (V)	No specific damages reported.

Structure description	Isolation system***	Year of construction	Acceleration H, V / Distortion	Behaviour during earthquake
Technical Research Institute, Matsumura-Gumi Corporation, Kobe, Hyogo, Japan Structural frame: Three-storied reinforced concrete building Structural plan: 10m x 16 m Distance from the epicentre: 35 km * Located close to the previous building	High-Damping Rubber Bearing (□□600/700) [4/4 units]	1994	Base: 0.272G (H1), 0.265G (H2) and 0.232G (V) 1FL: 0.148G (H1), 0.253G (H2) and 0.266G (V) RFL: 0.198G (H1), 0.273G (H2) and 0.334G (V) * In the non-isolated building located close to the seismically isolated building. RFL: 0.965G (H1), 0.677G (H2) and 0.368G (V)	No specific damages reported. A non-seismic isolated building, configuration of which is identically similar to the seismically isolated building, is located next to the building.
Niigataken Chuetsu Earthquake of October 23, 2004; M = 6.8				
Nursing Home for Senior Citizens, Ojiya Hospital, Ojiya, Niigata, Japan Structural frame: Five-storied reinforced concrete building Structural plan: 34.5m x 34.95m Distance from the epicentre: 6km	Natural Rubber Bearing (□ 600/700) [18 units]; and Slider Bearing with Elastomer (□ 400/650) [21 units]	1997	Base: 0.740G (H1), 0.808G (H2) and 0.487G (V) 1FL: 0.198G (H1), 0.205G (H2) and 0.749G (V)	No apparent structural damage. No damage to inside equipment. Objects inside building did not fall down. Opposite results were observed in neighbouring non-seismically isolated buildings.

Structure description	Isolation system***	Year of construction	Acceleration H, V / Distortion	Behaviour during earthquake
Hokuriku Vocational Training School, Nagaoka, Niigata, Japan (School Building) Structural frame: Eight-storied reinforced concrete building Structural plan: 22.5m x 33.0m Distance from the epicentre: 13km	High-Damping Rubber Bearing (□ 850/900/1000) [6/4/7 units]	1997	B1FL: 0.189G (H1), 0.239G (H2) and 0.150G (V) 1FL: 0.116G (H1), 0.141G (H2) and 0.143G (V) 8FL: 0.122G (H1), 0.162G (H2) and 0.180G (V)	No specific damages reported.
Mendoza West Argentinian Earthquake (2006) M 5.7				
Mendoza Technical National University Campus Two similar close located RC Frame Buildings: 8.2m X 8.7m X 8.6m. The first one is isolated (I) and the second one rigidly supported (NI). W = 3200 kN Location: 30 km from epicentre.	"I" Building based on four 3D Spring elements of 1000 kN Weight Capacity each in parallel with four 3D visco-dampers VD426	2004	Base PGA = 0.12g. Distortion in springs and dampers 3.0 mm. Constant acceleration along the isolated building height. Comparative seismic experimental measurements at "NI" and "I" buildings' roofs: Xni/i = 0.25/0.05g Yni/i = 0.4/0.06g Zni/i = 0.06/0.07g	No structural damage. 3D Acceleration reduction at the roof > 75% Structure: Axial forces reduction > 60%. Shear force reduction > 75% Bend. Moment reduction > 90% Story Drift reduction > 80%

Structure description	Isolation system***	Year of construction	Acceleration H, V / Distortion	Behaviour during earthquake
The Great East Japan Earthquake of March 11, 2014; $M_W = 9.0$				
Emergency Response Building, Fukushima DaiIchi Nuclear Power Plant Station, Ookuma-machi, Fukushima, Japan Structural frame: Two-storied steel-reinforced concrete composite structure building Structural plan: 52.6m x 40.6m Distance from the epicentre: 178km	Natural Rubber Bearing (□□1200) [10 units]; Lead Rubber Bearing (□ 1200) [4 units]; Sliding Bearing [31 units]; and Oil Damper [16 units]	2010	B1FL: 0.582G (H1), 0.756G (H2) and 0.446 (V) 1FL: 0.176G (H1), 0.213G (H2) and 0.516G (V) 2FL: 0.155G (H1), 0.185G (H2) and 0.621G (V)	No specific damages reported. After the earthquake, the building has been utilized for emergency response control building.
Emergency Response Building, Fukushima DaiNi Nuclear Power Plant Station, Naraha-machi, Fukushima, Japan Structural frame: Three-storied steel-reinforced concrete composite structure building Structural plan: 36.0m x 27.0m Distance from the epicentre: 183km	Lead Rubber Bearing (□□1200) [8 units]; Sliding Bearing [12 units]; and Oil Damper [4 units]	2010	B1FL: 0.411G (H1), 0.334G (H2) and 0.324 (V) 1FL: 0.184G (H1), 0.226G (H2) and 0.463G (V) 3FL: 0.154G (H1), 0.157G (H2) and 0.581G (V)	No specific damages reported.

Structure description	Isolation system***	Year of construction	Acceleration H, V / Distortion	Behaviour during earthquake
Test Laboratory Building, Tohoku University, Sendai, Miyagi, Japan Structural frame: Three-storied reinforced concrete building Structural plan: 6.0m x 10.0m Distance from the epicentre: 177km	High-Damping Rubber Bearing (□□435) [5 units]	1986	Base: 0.241G (H1), 0.301G (H2) and 0.243G (V) 1FL: 0.219G (H1), 0.362G (H2) and 0.280G (V) RFL: 0.244G (H1) and 0.344G (H2) * In the non-isolated building located close to the seismically isolated building. 1FL: 0.258G (H1), 0.327G (H2) and 0.249G (V) RFL: 0.824G (H1) and 0.702G (H2)	No specific damages reported. A non-seismic isolated building, configuration which is identically similar to the seismically isolated building, is located next to the building.
Computer Centre, Izumi Denryoku Building, Sendai, Miyagi, Japan Structural frame: Five-storied reinforced concrete frame structure Structural plan: 49.0m x 38.0m Distance from the epicentre: 178km	High-Damping Rubber Bearing (□) [16/18/6 units]	1990	Ground Level: 0.417G (H1), 0.378G (H2) and 0.228G (V) B1FL: 0.327G (H1), 0.345G (H2) and 0.218G (V) 1FL: 0.183G (H1), 0.177G (H2) and 0.240G (V) 3FL: 0.139G (H1), 0.174G (H2) and 0.489G (V) RFL: 0.199G (H1), 0.224G (H2) and 0.768G (V) * In the non-isolated administration building located close to the seismically isolated building. RFL: 1.054G (H1), 1.043G (H2) and 0.718G (V)	No specific damages reported. A non-seismically isolated administration building is located next to the building.

Structure description	Isolation system***	Year of construction	Acceleration H, V / Distortion	Behaviour during earthquake
Shinonome Condominium Building, Tokyo, Japan Structural frame: Thirty-six storied high-rise reinforced concrete frame building Structural plan: 42.6m x 43.1m Building height: 114.65m Distance from the epicentre: 385km * The seismic isolation system is installed at the intermediate story level of the building. The devices are placed between the stories No. 3 and No. 4.	Lead Rubber Bearing (1200x1200/1100x1100/1000x1000) (rectangular cross-sectional bearing) [12/6/22 units]; and Natural Rubber Bearing (1300x1300/1000x1000) (rectangular cross-sectional bearing) [3/8 units] * Another set of three units of elastic sliding bearings (□ 400) are placed at the bottom of the elevator shaft.	2011	Ground level**: NA (H1), 0.177G (H2) and NA (V) 1FL: 0.085G (H1), 0.114G (H2) and 0.040G (V) M4FL: 0.109G (H1), 0.129G (H2) and 0.043G (V) 4FL: 0.075G (H1), 0.100G (H2) and 0.047G (V) 36FL: 0.092G (H1), 0.116G (H2) and 0.095G (V) ** NA: Not available at the time.	No specific damages reported.

Note * Two horizontal components, being orthogonal with each other, are represented by (H1) and (H2), and one vertical by (V), respectively.

Note ** Letter “G” in “Acceleration column” indicates the gravity of acceleration and in the table herein is taken to be 1,000cm/s^2, i.e., 0.123G represents 123cm/s^2 in acceleration.

Note *** Symbol □ is used to indicate a square shape.

ANNEX IV COUNTRY REPORTS

The country reports presented in this Annex have been prepared from the original material as submitted by the contributors and have not been modified or edited by the staff of the IAEA. The views expressed remain the responsibility of the contributors and do not necessarily reflect the views of the IAEA or its Member States.

IV-1. REPORT FROM FRANCE

SEISMIC ISOLATION OF NUCLEAR STRUCTURES – OVERVIEW OF THE FRENCH PRACTICE AND EXPERIENCE (from Transactions SMIRT-22, San Francisco, 2013)

ABSTRACT

The present paper gives an overview of the best practices and the experience of the French industry, gained over the last 30 years, to implement seismic base isolation systems under nuclear facilities. It contains (a) a brief description of isolated nuclear facilities in France, (b) a point on the specific safety requirements attached to the isolation system, (c) an overview of the analysis methods for the design of the isolation system itself and the supported structures systems and components (SSC) and (c) a presentation of the technical solutions retained for the isolators.

INTRODUCTION

Since the recent seismic events in Japan, and especially the one affecting the Kashiwazaki-Kariwa plant in 2007, there is a global renewal of interest for seismic isolation. The field of application of this technology is often thought to be reduced to high seismicity sites whereas significant advantage could also be expected on moderate seismicity sites. France is a unique example of such moderate seismicity area where seismic isolation technologies have been used by nuclear operators (EDF, AREVA, CEA, ITER Organization) for nuclear facilities, including several power plants, experimental reactors, laboratories, enrichment facilities and spent fuel pools. The use of seismic isolation has been sometimes driven by cost reduction in the design, sometime by standardization purpose and sometimes by investment protection. Nowadays, benefit can also be taken from these systems for the demonstration of the robustness of installations to Beyond Design Earthquake (BDE).

The isolation technology used in France, since the late 70s, is polychloroprene laminated rubber bearings, which would today be referred to as low damping rubber bearings (LDRB). The quality of manufacturing, the management of the qualification process, the tolerances of construction and the knowledge of the material behavior over time have evolved since the first use of this technology. The concept and the material composition itself have essentially been kept constant.

The present paper gives an overview of the best practices and the experience of the French industry, gained over the last 30 years, to implement seismic base isolation systems under nuclear facilities. It contains a brief description of isolated nuclear facilities in France, a point on the specific safety requirements attached to the isolation system, an overview of the analysis methods for the design of the isolation system itself and the supported structures systems and components (SSC) and a presentation of the technical solutions retained for the isolators.

A more detailed synthesis is also being prepared by the authors of the present paper to support IAEA in its effort to issue guidelines on seismic isolation systems for nuclear facilities. This synthesis will be available in AFCEN (2015).

SEISMIC ISOLATION IN FRANCE - PRACTICAL EXAMPLES OF ISOLATED FACILITIES

Seismic base isolation systems, for nuclear power plants and facilities, are aimed at decreasing the dynamic loads on SSC by either (a) filtering the seismic excitation by the insertion of soft devices below the isolated structure, (b) decreasing the response amplitude of the isolated structure by addition of damping, or (c) cutting off the acceleration excitation amplitude by allowing free displacement of structures above a given threshold. In France, given the moderate seismicity of the sites where nuclear structures are located, filtering the seismic excitation was found to provide an adequate answer to the design challenges, without the use of additional damping or cutting off systems.

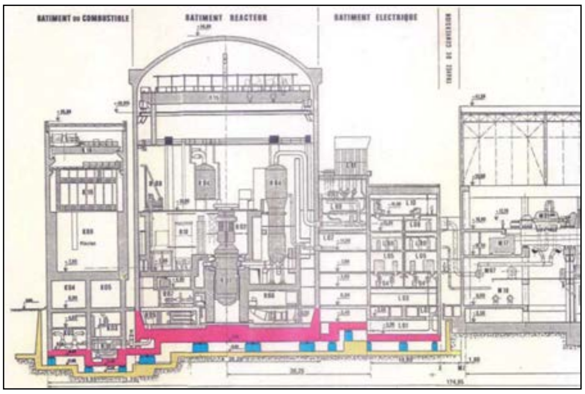
Different types of isolators can be found in the civil engineering industry, depending on the ability of the bearings to transmit shear and/or traction. However, all the existing seismically isolated nuclear structures in France are based upon the same isolation system, transmitting shear loads and compression but not tension forces. The bearings are constituted of alternate layers of polychloroprene rubber (CR) and metallic sheets.

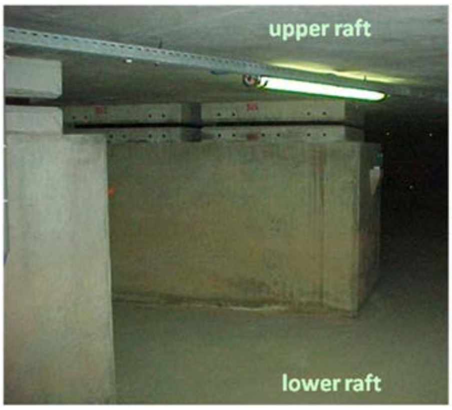
This type of bearings was invented by Eugène Freyssinet in 1952. Since then, countless bridges have been built supported by elastomeric bearings. These structures are constantly subjected to environmental attacks, thermal variations and loads variations. This technology of bearings had therefore been widely challenged over several decades and was logically selected to seismically isolate the Cruas NPP in the late 70s, see Figure A-1. La-Hague fuel reprocessing plant followed then with the isolation of its fuel storage pools. Nowadays, all nuclear projects built on seismic isolation do integrate the feedback from Cruas and La-Hague projects to design their own isolation system.

Table A-1 gives an overview of the major nuclear projects built on seismic base isolation systems in France (see Figures A-2 and A-3). It can be seen from this table that the size of the isolators has been gradually increased over time, whereas the isolation frequency tends to decrease. This reflects the improvements made in the manufacturing process and in the control of the in-core mechanical characteristics of the isolators. For all projects, laminated polychloroprene rubber bearings were selected as the isolator technology. The dynamic behavior of the polychloroprene isolator is quasi-linear when subjected to an earthquake loading. Its equivalent damping is around 6 %.

Table A-1: Synthetic description of isolated nuclear facilities in France

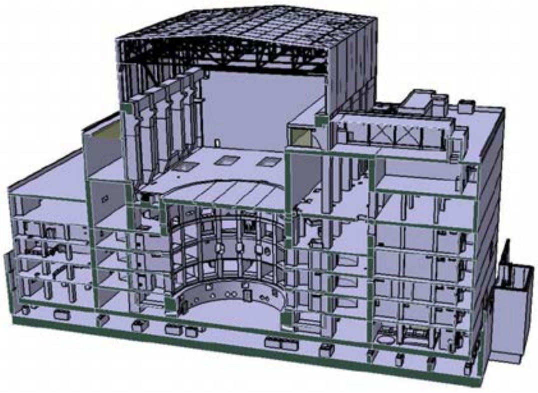
Facility	Beginning of operation	PGA	Design isolation frequency	Isolators size	Shape factor	Dynamic shear modulus
Cruas-Meysse NPP 4 x 900MWe PWR units	1984	0.3 g	1 Hz	500 x 500 x 66.5 mm square bearing	9.26	1.1 MPa
LaHague Spent Fuel Pools	1985	0.2 g	0.85 Hz	700 x 700 x 147 mm square bearing	17.5	1.1 MPa
Georges Besse II Enrichment Facility	2010	0.3 g	NC	cylindrical bearings d=500 mm h=400 mm	NC	0.7 MPa
Jules Horowitz Research Reactor (JHR)	In construction	0.32 g	0.6 Hz	900 x 900 x 181 mm square bearing	11.25	1.1 MPa
International Thermonuclear Experimental Reactor (ITER)	In construction	0.32 g	0.55 Hz	900 x 900 x 181 mm square bearing	11.25	1.1 MPa





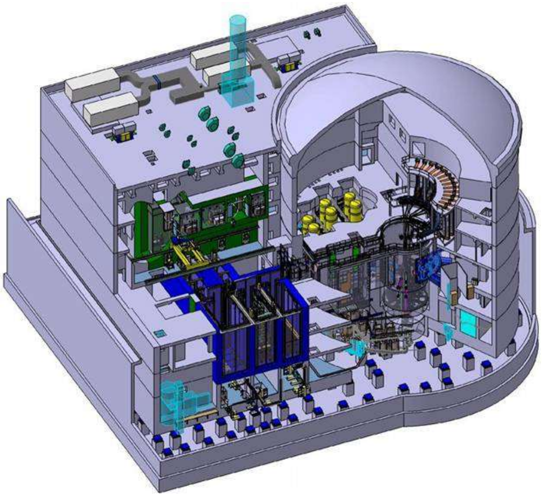
(a) (b)

Figure A-1. Cruas NPP (a) Global cut view (b) Seismic base isolation system – Courtesy EDF



(a) (b)

Figure A-2. ITER (a) Global cut view (b) Seismic base isolation system – Courtesy ITER Organization



(a) (b)

Figure A-3. Jules Horowitz Reactor (a) Global cut view (b) Seismic base isolation system – Courtesy CEA

SAFETY REQUIREMENTS

Implementing a seismic isolation system on a nuclear structure adds a new system to the installation which Safety must be demonstrated in all design conditions. This system supports the whole structure and determines its seismic response. All Safety requirements applying to a non-isolated nuclear facility are equally applicable to an isolated facility. Their fulfillment is generally greatly simplified by the use of a seismic isolation system. Some additional requirements are specific to seismically isolated structures. These include: (a) prevention of the seismic isolation system failure modes, (b) management of the ageing of the isolators characteristics and (c) control and replaceability of the isolators.

Prevention of the seismic isolation system failure modes

A particular attention is paid to prevent the possible failure modes of the isolation system itself. These include:

(a) Excessive shear deformation of the isolators due to the horizontal seismic load. The failure occurs when the shear forces between the rubber layers becomes too high, ultimately leading to a de-lamination. It is generally observed for a distortion (ratio of the horizontal displacement to the total rubber thickness) higher than 350% for the CR bearing used in France, refer to Kawamura et al (1988) and Mizukoshi et al (1992). This failure mode is prevented by taking sufficient margin to the rupture at the design stage.

(b) Buckling of the bearing under combined vertical and horizontal seismic loads. This failure mode is unlikely because the thickness of the bearings is generally low compared to its other dimensions. Such shape factor is necessary for carrying the weight of usual nuclear structures.

(c) Excessive tension of the isolators due to seismic loads. The vertical seismic loading cumulated with the rocking effect due to the horizontal seismic loading can decrease the compression within the bearing. This can generate a global tension in some of the peripheral bearings, potentially leading to rubber failure. Even though rubber bearings do have some capacity to accommodate tension loads, this capacity has never been credited in the design of isolated structure and margins were taken relative to the risk of tension within a bearing. As a design option, such failure mode can also be avoided by allowing uplift between the upper basemat and the isolators.

(d) Loss of bearing capacity due to fire. This failure mode is prevented by an adequate site protection and by systems that keep potential fire sources outside the open space below the super-structure. Moreover, the rubber mixture in itself can be selected for its flame-retardant properties (as CR is).

(e) Loss of bearing capacity of the Pedestal due to excessive loads transmitted by the isolators. This failure is prevented by applying building design codes with sufficient margins and by robust design of the Pedestals.

Management of the ageing characteristics of the isolators

Since the first use of seismic isolation systems for nuclear facilities in France, the question of ageing of the polychloroprene material was raised, see Coladant (1993). Predictions of the ageing were made but these predictions were based on the limited knowledge available at that time. In the civil engineering industry, the polychloroprene bearings were submitted to largely different environmental conditions from the one below a nuclear facility. Moreover, they were replaced when necessary or regularly; so that they did not provide any information about the ageing of polychloroprene after several decades.

As a consequence, it was requested to monitor the ageing of the isolators throughout the lifetime of the nuclear facilities. This monitoring was achieved by placing samples of isolators next to the actual ones, below the super-structure in the same environmental conditions, and by pre-stressing them with the same compressive stress as the one experienced by the actual devices. On a regular basis, some of these samples have been extracted and tested. These tests showed that the isolators' characteristics were still within an allowable range and that they will remain so until the end of life of the installations. Indeed the only significant variation was found to be an increase of shear modulus of the polychloroprene, which is stabilizing with time, and which was never measured above 40% whatever the conditions and the samples size (that is an 18 % shift in the isolation frequency which may increase the acceleration applied to the facility). A slight decrease of the rubber bearing damping value was also observed, with no significant consequences.

The samples historically used for the monitoring of ageing characteristics were of reduced size compared to the actual isolators, which tends to accelerate the ageing effects. Moreover, the compression may not have been maintained in such an efficient way in the sample as in the actual isolators, which again maximizes ageing effects. Therefore, the tests performed on these samples provide a conservative estimate of the characteristics variations.

Nowadays, accelerated ageing tests do reproduce the stiffening effect and can be compared to an experimental database consisting in all the tests performed on monitoring samples. Monitoring of the ageing characteristics of isolators is still required for new facilities. This monitoring will likely be made on full scale isolators instead of reduced samples as far as dynamic testing capacities of laboratories are available. Finally, a conservative assumption of the stiffening of the isolation device over the lifetime of the facility is used at the design stage. All design analyses are made considering both beginning of life and conservative end of life stiffness of the isolators.

Control and replaceability of the isolators

In the 70s and early 80s, when seismic isolation systems where first implemented for nuclear facilities and power plants in France, such systems were not meant to be replaceable. For the Cruas NPP, it has been a request from the French Safety Authority to demonstrate that such replacement was possible. A replacement operation was carried out on a single pedestal supporting 2 isolators to make this demonstration in the 90s.

Nowadays, it is a Safety requirement that isolators should be replaceable. Dedicated technologies were implemented on the JHR and ITER project to make such replacement easier.

A regular control of the isolators, including their mechanical characteristics, is mandatory and is part of the maintenance plan of the installation.

DESIGN METHODS

Design of the isolators

The isolators and their connections to the structure are designed in such a way that their performances fulfill the Safety requirements, with an adequate degree of reliability. This includes a guarantee of the proper behavior of the isolation system during the life time of the plant, in its mechanical, physical and chemical environment, as well as in accidental conditions. It does also include the prevention of the different failure modes of the system under design accidental load cases and in beyond design accidental conditions (such as BDE). The design must also ensure the ability to perform routine inspection, and, if needed, replacement of the isolators during the service life of the plant.

In addition to the service loads, the isolators shall accommodate creep, concrete slab shrinkage, construction sequence and thermally induced displacements. Design methodology and criteria come from seismic design standards for conventional civil structures such as EN 1998-1:2004 (Eurocode 8: Design of structures for earthquake resistance– Part 1: General rules, seismic actions and rules for buildings), EN 1998-2:2005 (Eurocode 8: Design of structures for earthquake resistance – Part 2: Bridges), EN 15129:2010 (Anti-Seismic Devices) and EN 1337-3:2005 (Structural bearings, Part 3: Elastomeric bearings).

Additional safety margins (beyond the safety coefficients defined in the standards) or additional criteria (coming from the know-how and the feedback from previous applications) are taken into account for nuclear projects in addition to the standards requirement. A detailed review of the criteria applied for the design the most recent French projects of seismic isolation is given in AFCEN (2013).

During preliminary design stage, the loads on the isolators are sometime estimated from a simplified model of the isolated structure with an infinitely stiff representation of the basemat. Although giving good estimates for the preliminary design, this approach may lead to significant bias in the results. Therefore, at the detailed design stage, the loads shall be determined based on:

(a) A detailed 3D study of the seismic response of the whole structure, in order to address the impact of the coupling between vertical and horizontal responses and local flexibilities of the basemats and the structure.

(b) A complete time-based calculation of the structure, to address the effect of the shrinkage and of the construction sequence on the vertical loads on the isolators.

(c) Consideration of the temporary load case due to the propping of the upper basemat during the replacement of an isolator. Indeed, this temporary step can induce significant modifications of the bending in the reinforced concrete section.

The mechanical characteristics of the isolators considered in the design can be extracted from the qualification process, if this qualification is performed at the early stage of the project. Beginning of life and end of life values are used as bounding conditions for the life time of the plant.

Design of Structures, Systems and Components (SSC)

The design of SSC within a seismically isolated structure is largely similar to the one in any other nuclear structure. The same design codes apply. Since the type of isolation system used in France is Low Damping Rubber Bearings, the structure analysis can be carried out either with a response spectrum analysis or with a linear time history analysis (i.e. modal superposition analysis). The main specificity comes from the necessity to consider beginning of life and end of life values for the mechanical characteristics of the isolation system. The use of a 3D model for the structural analysis is mandatory in order to correctly account for torsion effects.

The generation of in-structure floor response spectra shall be performed with a 3D model as well, with simultaneous excitation in the three spatial directions. Indeed, the in-structure floor response spectrum in one horizontal direction comprises:

(a) An excitation at the frequency of isolation corresponding to the global displacement of the isolated structure. This excitation produces a first peak on the horizontal floor response spectra, which is essentially constant on all floors of the structure.

(b) An excitation at higher frequencies due to the vertical and rocking modes of the structure. These modes are not filtered by the isolation system and result in local horizontal accelerations. This excitation produces one or several peaks on the floor response spectra in a frequency range similar to the one observed on the vertical floor response spectra, see Politopoulos et al (2011) and Moussallam et al (2011).

In the vertical direction, there is no difference in nature between an isolated and a non-isolated structure, even though the presence of a seismic isolation system could modify the vertical response of the isolated structure.

Because of the large displacements induced by the seismic isolation systems, all connections between the isolated part and the rest of the facility must be designed with adequate compensation capabilities. Several technological solutions exist to provide the necessary flexibility. They include gimbals joints for large diameter pipes and loops for small diameter pipes.

TECHNICAL SOLUTIONS AND MATERIAL CONSIDERATIONS

Applicable standards

Some standards concerning isolators, and more specifically laminated rubber bearings, are applicable for bridges and conventional buildings. These standards offer an interesting base for nuclear applications since they have been engendered by many years of practice. Nevertheless, the EN standards, written to harmonize and standardize engineering and supply practice over Europe, do now constitute the reference. CE accreditation for isolators is based, among other criteria, on the Initial Type Testing (ITT) results of the rubber mixture involved in the isolators' design. EN standards give requirements on geometry and mechanical properties of the isolators but also on elastomeric rubber. Once the ITT qualification is passed, the producer can use a CE marking for all the bearings produced with this mixture and on all its projects. The global same approach is kept for nuclear application but adapted to high level quality requirements of Safety Important Components (SIC). It also means that the very detailed specifications of the EN standards may not be strictly followed since these specifications reduce the rubber choice and correspond to a technical compromise which might not be acceptable for SIC.

Reasons for the technological choice of chloroprene rubber

Laminated bearings have been industrially used since the early 50's in the construction of the motorways in Europe to standardize the bridges crossings. In France and Germany, the Polychloroprene Rubber (CR) has been chosen. In some other countries, Natural Rubber (NR) has been used mainly for costs issues or because of very low temperature area (north USA for example) as its glass transition temperature is lower than CR. In the following, the term NR will not refer to pure natural rubber (damping of which is between 2% and 4%) but to regular NR additive-based compound used by the elastomeric bearing industry.

The rubber material compound needs to be chosen in accordance with the specific project requirements (environment, hazard…). Both NR and CR can be used as bearing material but they have different behavior. Generally speaking, NR has a better elongation and lower hardness whereas CR has a higher tensile breaking load and a higher hardness. The Safety-related behaviors which differentiate these two rubbers are:

(a) Fire resistance capacity: Fire resistance capacity of the CR is better than natural rubber NR. Indeed, the CR is flame-retardant (auto-extinguishable) whereas the NR burns by itself. DuPont (2004) provides examples of such rubber compounds.

(b) Ageing resistance: The rubber mechanical properties will change over the time due to ageing. Ageing is a slow process occurring in the peripheral material, mainly due to air and ozone attacks. NR stiffens over time as the rubber molecules continue to cross-over slowly at room temperature. As a result, the effective shear modulus of the bearing increases. The CR is known as a robust type of elastomeric, especially against ozone and air attacks, see SETRA It stiffens at a .(2000) slower rate than NR. To a general extent, CR has better mechanical resistance against environment attacks as the reaction of oxidation is slowed down by the molecules of the CR compound, contrary to NR.

(c) Resistance against thermal hazard: Under cold-temperature conditions, the mechanical properties of the NR are more stable than those of the CR (rubber stiffness increases when temperature decreases). It is a common practice to forbid CR beyond -10°C / -20°C. Yakut et al (2000) addresses this issue. For nuclear application, the isolators are protected from weather conditions in the controlled space between the upper and the lower basemats. As a consequence the temperature is very stable.

(d) Resistance against scragging: In the range of distortions and isolation frequencies, no scragging effect (stiffening of the compound under cycling) can be noted on neoprene-based compound. This issue is treated at the qualification stage to fulfill the standard requirements of EN 15129:2010.

(e) Resistance against radiation: Neoprene-based compound (i.e. CR) is known to have a good resistance to radiation, see Lee (1985). The upper basemat casted on the top of the isolator generally provides a thick shield protecting isolators from radiations.

(f) Creep resistance: Creep resistance of rubber bearing has been widely demonstrated on numerous applications; see Hamagushi et al (2009) for instance.

Determination of the mechanical characteristics of the isolators

The shear modulus is measured in both static and dynamic conditions. Full-scale static and dynamic tests are performed to confirm the vertical and rocking characteristics (stiffness and damping). In order to guarantee the required quality of elastomeric rubber, the following tests are performed:

(a) Effect of shear strain amplitude,
(b) Effect of frequency,
(c) Effect of temperature,
(d) Shear modulus and damping after accelerated ageing,
(e) Stability of shear properties under repeated cycles,
(f) Shear bond test,
(g) Resistance to low temperature crystallization (if any),
(h) Resistance to slow crack growth.

Focus on ageing

Durability is a key issue of the nuclear projects. The effect of ageing has a major impact on long-term mechanical properties deviations. Temperature, chemical environment (hydrocarbon…), ambient air (ozone and air), radiations are some of the external conditions driving the ageing of the isolators. However, for NPP isolation, air attack is the main parameter causing CR and NR ageing. Isolators are subject to environmental attack through their external surfaces only. The surface exposed should therefore be small compared to the size of the bearing: the first shape factor S (which corresponds to the ratio between the surface of rubber sheet under compression and its free lateral surface) is the relevant parameter to evaluate the robustness of the isolator against oxidation. The oxidation depth is limited to a few centimeters inside the bearings. Indeed oxidation is located in a relatively thin slice around the bearing and most of the isolator remains anaerobic.

The methodology commonly used to model the long-term mechanical properties ageing process is based upon Arrhenius equation (refer to ISO 11346:2004 and appendix F1 of EN 15129:2010 .(Arrhenius equation is a simple formula to assess the temperature-dependence of the reaction kinetics the temperature accelerates the chemical oxidation process which shifts the mechanical properties of) the rubber). Appropriate tracers needto be used to monitor the evolution: shear modulus (static and dynamic) is commonly used. The more the temperature increases, the shorter the ageing test needs to be for the tracer to reach a given deviation. The experimental process is thus to submit isolators or samples to several duration / temperatures and perform regularly tracer measurement (at ambient temperature). The tracer variations are then plotted versus the duration and post-processed using Arrhenius equation.

The representativeness of the methodology needs to be carefully addressed especially regarding the following issues:

(a) The applicability of the Arrhenius equation shall be demonstrated (correlation of the affine function model and the plotted points). At least three different temperatures shall be used, see Figure 4 and 5 for an example of such demonstration.

(b) The deterioration mechanism shall remain the same in the range of the tested temperatures (range of validity of Arrhenius equation). The risk is that too high temperatures may initiate other damaging mechanisms than the one observed in the normal environment of the isolator – these mechanisms would then pollute the measurements.

(c) The sample size (if any, instead of full-scale isolator) and its external surface exposure need to be realistic. The shape factor and the exposed region need to be in accordance with the full-scale bearing.

Finally, it is recalled that the ageing models should be complemented by a monitoring of the actual ageing of the isolator (see paragraph on safety requirements). Monitoring results can be used to update the ageing model if needed.

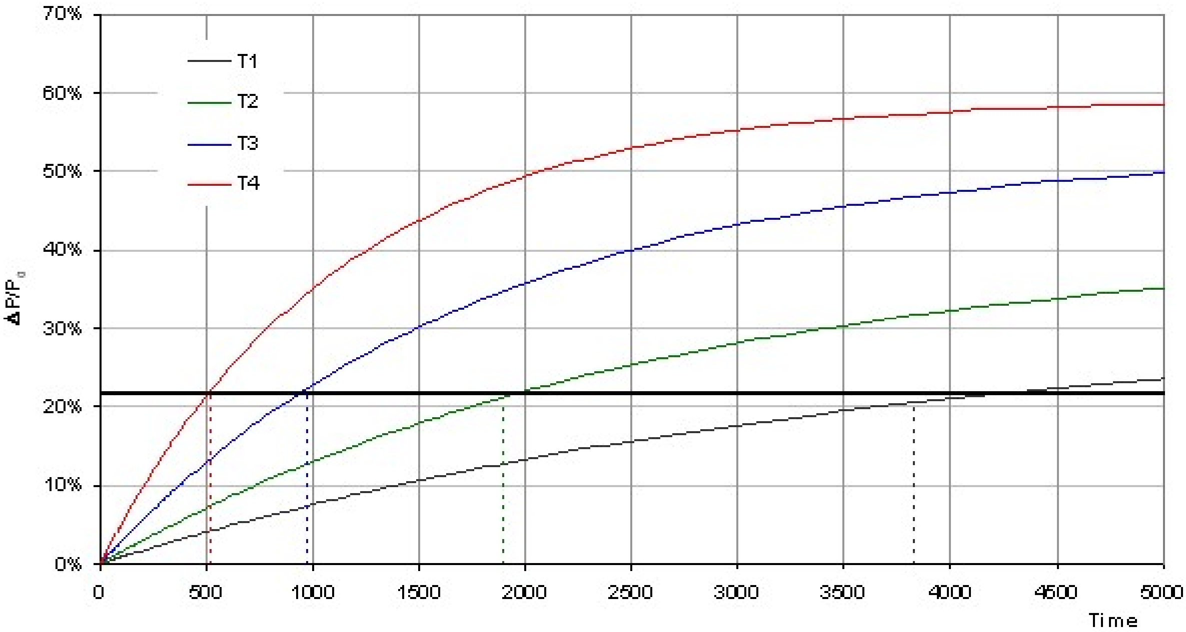


Figure 4. Example of a typical isothermal variation of a tracer versus ageing duration

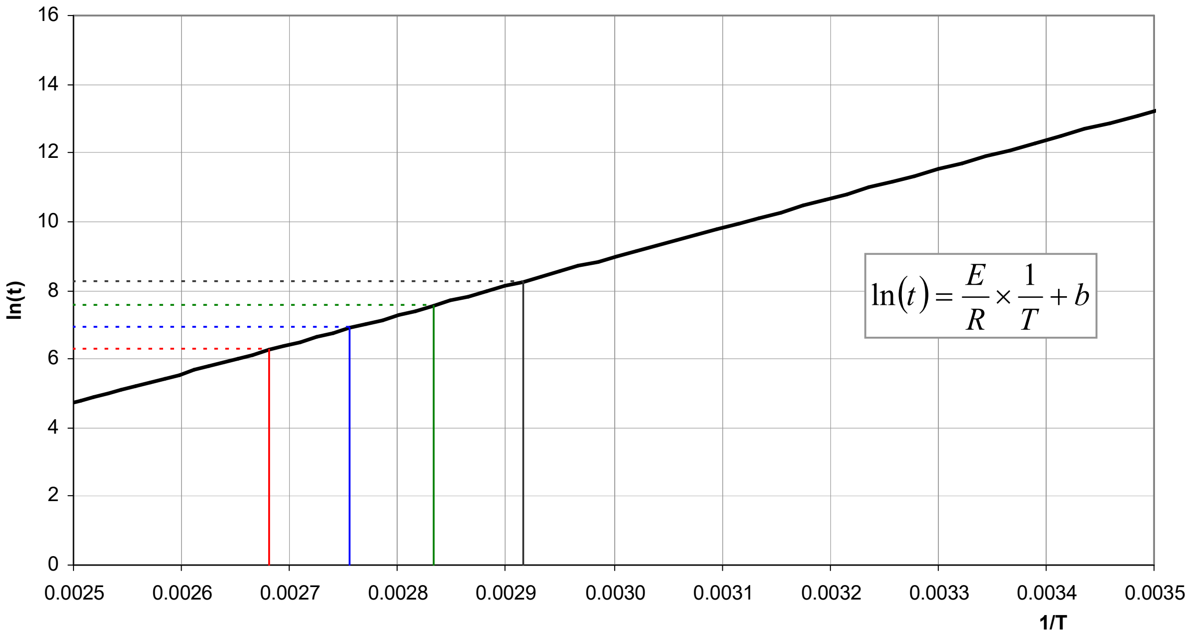


Figure 5. Example of a typical Arrhenius post-processing of the tracer isothermal curves – Affine slope with E, activation energy of the reaction in J/mol and R, Boltzmann constant expressed in units of energy (R = 8.314 J/mol.K), T the temperature and t the time.

CONCLUSION

After more than 30 years of use of seismic isolation systems for the nuclear industry in France, significant experience has been gained in designing, manufacturing, installing and monitoring these systems. Because of the new international interest expressed for this type of technology, the French industry, from plants owner to isolators manufacturer have joined in a common effort to share this experience with the international community. The present paper is part of this effort. A more complete picture will be given in AFCEN (2013).

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IV-2. REPORT FROM GERMANY AND RUSSIAN FEDERATION

3-D Base-Control Systems in Power Plants – Russian / German Experience

1 INTRODUCTION

1.1 General

Power plant machinery can be dynamically decoupled from the substructure by the effective use of vibration isolation systems. These isolation systems can be used in turbine foundations, coal mills, boiler feed pumps or other equipment foundations to mitigate the transmission of operational vibration. The application of helical steel springs and viscous dampers as elastic support systems may also be used to protect against earthquakes and other catastrophic events, such as airplane crash. This article illustrates basic principles of 3-dimensional elastic support systems and applications on power plant equipment and buildings in medium and high seismic areas.

1.2 Basics of Seismic Isolation with a 3-D Base-Control System (BCS)

The Base-Control System (BCS) consists of helical steel springs, which are arranged underneath the base plate of the structure. Additionally to the spring elements highly efficient Viscodampers are arranged. The system is flexible in the horizontal directions, but possesses also vertical elasticity. The Viscodamper supplies absorption forces in the horizontal and vertical directions. Due to the implementation of spring elements the mode shape of the structure is changed and the predominant frequency of the system is reduced (= increase of fundamental period of vibration).

The second measure in utilizing passive seismic control systems is based on the increase of damping. This method may be combined with the frequency reduction. The reduction of the induced structural responses by the increase of viscous damping can be taken from different national and international standards. In particular the resulting demands (e.g. accelerations, base shear etc.) of the structure can be significantly reduced by using the BCS. The main characteristics of the BCS are shown below:

Table 1. MAIN CHARACTERISTICS OF A BCS.

elements are pre-stressable
no min. load of the superstructure required
relatively small horizontal displacements / relatively small vertical displacements at corners
high efficiency in regard to horizontal effects / high efficiency in regard to vertical effects
properties of the devices can be adjusted to the project requirements / adjustable in regard to the mode shape and the corresponding damping (in vertical and horizontal directions)
small loads acting on the substructure / superstructure
no effect on higher modes
no aging, no change of properties, regular visible inspection recommended
access, inspection, adjustment & exchange of devices is possible, if required
integration of vibration isolation, isolation of structure borne noise and protection against airplane crash

Spring elements with helical steel springs possess linear-elastic behavior in both horizontal and vertical directions. There is nearly no dependency between the horizontal and the vertical stiffness of the spring devices. The horizontal stiffness is equal for both horizontal directions. Therefore, their numerical description is comparatively simple and the behavior of the structure on these devices can easily be assessed. The elements are carrying the dead load of the structure and are designed to have sufficient safety margin to bear also additional loads (in both horizontal and vertical directions) from seismic excitation. There is no deviation between the static and dynamic characteristics of the steel springs.

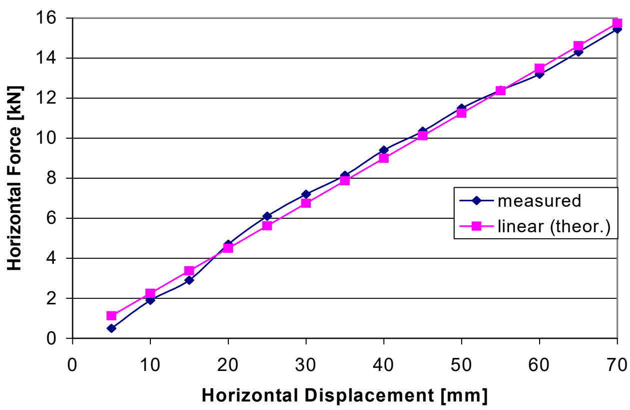

Figure 1. TYPICAL SPRING ELEMET AND EXAMPLE OF MEASURED PARAMETER.

The viscous dampers supply high damping forces, which are high velocity-proportional. The properties of these dampers can be described by the damping resistance values in all spatial directions. Viscodampers, installed beside the spring elements, have the task to absorb the kinetic energy. The implementation of them lead to an increase of structural damping and they serve as a displacement limitation of the structure and the devices themselves.

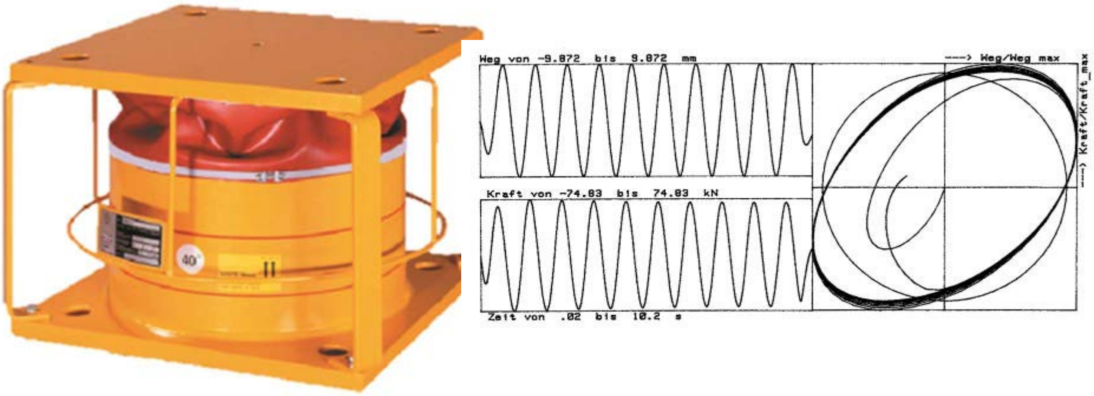

Figure 2. TYPICAL DAMPER AND EXAMPLE OF MEASURED PARAMETER.

The theoretical investigations of the efficiency of a Base Control System have been verified by experimental investigations (Rakicevic et. al., 2006).

2 APPLICATIONS OF BASE CONTROL SYSTEMS

First applications of the ‘Base Control System’ have now been in use for more than 20 years. They have proved their efficiency, for instance, during the Northridge earthquake, California in 1994. These systems have been used to provide earthquake protection (seismic isolation) of power plant machinery, equipment, and NPP buildings. More details about these applications can be found in “Earthquake Protection Strategies for Power Plant Equipment” and “3-D Base Control Systems for the Seismic Protection of Power Plant Equipment and Buildings” by Peter Nawrotzki.

In protection of NPP buildings - the efficiency of the BCS for building structures can be seen in the following plots (Figure 3) from a feasibility study, showing the floor response spectra at an elevated position of a building structure. In one case (“WITHOUT BCS”) the building is supported by fixed restraints at the basemat in the second case (“WITH BCS”) the same structure is supported by a BCS. A time-history analysis is used for the calculation of the system response due to a seismic event.

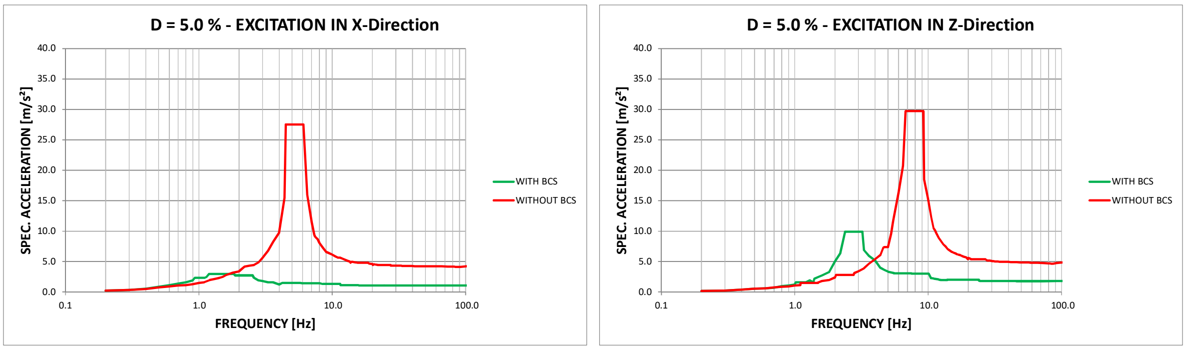

Figure 3. FLOOR RESPONSE SPECTRA FOR HORIZONTAL AND VERTICAL DIRECTIONS.

The red lines in Fig. 3 display the floor response spectra at one location inside the building structure without BCS. In the same graphs, the green lines show the floor response spectra at the building with BCS. All curves consider a spectrum widening of 15%. Due to the authoritative eigenfrequencies of the spring supported system – approx. 1,1 Hz for the first horizontal mode shape and approx. 3,0 Hz for the vertical mode shape, a small narrow peak around these frequencies is unavoidable. Above these frequencies the floor response spectra of the building with BCS are significantly lower than the floor response spectra of the unprotected building. This efficiency provides an important advantage for the design and layout of equipment, which has to be installed inside the structure.

Base-Control Systems significantly improve the seismic performance. In comparison to base isolation systems, e.g. with rubber bearings, they also work in the vertical direction as there is sufficient vertical flexibility provided by the spring system.

3 LOAD CASES OTHER THAN SEISMIC

Usually the seismic load case is not the only governing case for the design of a structure. For nuclear power plants for example an airplane crash is an important emergency load case to consider. Several structures or equipment inside the building should be protected against this load case. The detailed experience with the elastic supports of hammers in the forging industry lead to the idea, that spring elements and viscous dampers could be also used for the protection of a structure against shock input due to airplane crash.

The mentioned forging hammers are designed to generate large dynamic forces with every hammer blow. This load case is similar to the load case airplane crash regarding general load-time history. Helical steel springs and dampers effectively isolate hammer vibrations, and bring the hammer to rest before the next blow. Due to the low frequencies of the spring supported structure the high frequency content of the impact is filtered out.

The elastic support of network cabinets in a NPP provides a seismic control system and a protection system against airplane crash at the same time. Figure 4 shows the efficiency of a BCS for these cabinets in horizontal and vertical directions in regard to excitation by earthquakes and airplane impact. The dotted lines in Fig 14. represent the response spectrum (“RSP”) curves below the elastically supported system. These curves are used as an input for the system.

The solid lines in the figures display the response spectrum curves on top of the devices, showing the characteristics of the behaviour of the system. Apart from the unavoidable small area around the natural frequency of the elastically supported system, the BCS is capable to reduce the acceleration values significantly in nearly the whole frequency range. Regarding the high frequency content of the airplane input the huge reduction of the spectral acceleration values could be an important advantage for the protected structure.

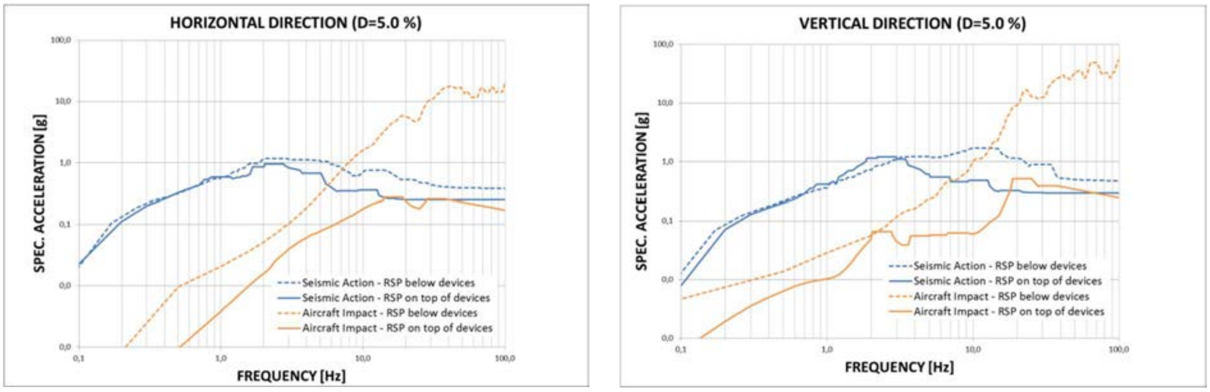

Figure 4. FLOOR RESPONSE SPECTRA FOR EARTHQUAKE AND AIRPLANE IMPACT.

In cases where the spring and damper devices are arranged in a foundation pit, it has to be ensured that flooding will not damage the elements. For the helical steel springs a corrosion protections system could be used, but water must not get into contact to the viscous liquid of the dampers. To protect the elements against flooding it is possible to place the elements on pedestals or equip the elements with a special enclosure like a diving bell. Pump sumps should be arranged in the pit additionally (first measure).

4 ACCESS, INSPECTION, POTENTIAL ADJUSTMENT AND EXCHANGE

An important advantage of pre-stressable spring elements is the fact that they can be adjusted and exchanged if required. Figure 5 shows the procedure of height adjustment by pre-stressing the elements and inserting steel shims. The elements are placed on top of concrete pedestals allowing easy access during inspection and adjustment if required.

Figure 5. ACCESS, INSPECTION, POTENTIAL ADJUSTMENT AND EXCHANGE OF DEVICES.

During foundation construction and machine foundation (in case of spring supported machine foundations), spring elements are usually pre-stressed and locked. This creates a rigid support during the entire installation period. Afterwards the elements are released. At this time general alignment and adjustment of single spring elements, if necessary, are done by adding or removing shims. This procedure of height adjustment could be used also in cases of differential settlement of the substructure or in cases where significant load changes of the supported structures occur.

5 QUALIFICATION PROCEDURES

Depending on the project specific requirements, certain qualification procedures have to be used. Helical steel springs can be calculated and designed according to DIN standards. Prototype tests are also possible. For the determination of the properties of viscous dampers the preparation of calculations is not feasible. It is required to perform prototype test of the dampers to ensure and verify the design values of these devices. In this regard special tests may be required in regard to influences by different temperature conditions, humidity, corrosion and/or radiation. For nuclear facilities it is essential to choose a suitable damper in regard to radiation effects. Figure 6 shows a typical example of viscous dampers in a NPP. The dampers shall fit present specifications as well as regulations like:

- Nuclear Power Plant Safety Guide (ОПБ-88/97, НП-001- 97),
- Nuclear Power Plant Design Standards (НП-031-01),
- KTA 3205.3.

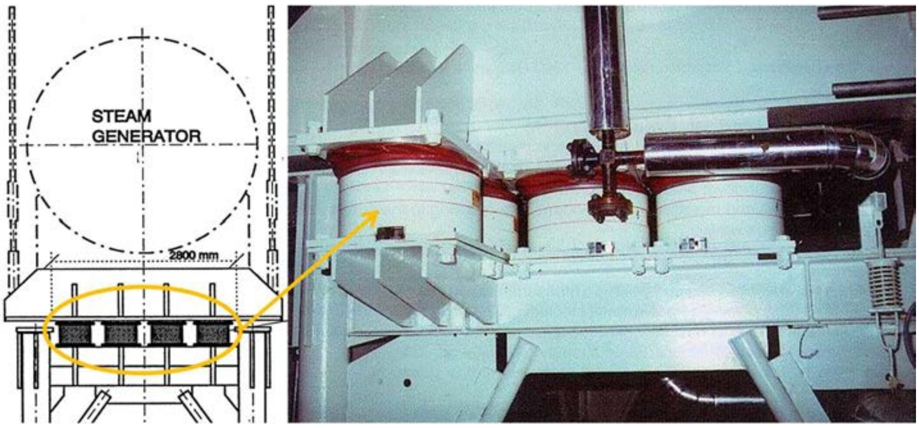

Figure 6. NPP BOHUNICE, SLOVAKIA, SEISMIC PROTECTION OF STEAM GENERATOR.

Beneath the required documents regarding the general qualification of the supplier of spring and damper devices it is at least mandatory to provide Quality Assurance Plans. These plans have to been taken as a basis for ensuring the quality assurance of the devices. The general qualification could consist of the following issues:

prototype testing / qualification,

production testing / quality assurance,

certification of Quality Management Standard,

certification of Environmental Management Standard,

certification of Occupational Health and Safety Management System,

documentation of the delivery capacity,

documentation of the required test equipment for the spring elements and damping devices,

test stands required for pre-qualification / and quality assurance.

6 CONCLUSIONS

This annex presents the methodologies and cases involving elastic support of heavy equipment which results in low system frequencies as well as high damping values. Base control systems improve seismic performance by significantly reducing accelerations and structural stresses.

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IV-3. REPORT FROM KOREA

Korean Research Activities for Seismic Isolation Applications in Nuclear Power Plants

1. BACKGROUND

The recent Magnitude 9 Great East Japan earthquake has increased concern for the seismic safety of nuclear power plants (NPP) to unprecedented levels. The precise intensity of ground shaking at a site during future earthquakes is very difficult to predict with certainty, and increased attention is being placed on the need to provide adequate safety during larger design level events, and even larger ones having very low probabilities of occurrence. Conventional design methods might well be used to achieve the desired levels of safety. However, this direct solution may introduce a wide variety of technical challenges due to the high forces and accelerations introduced in the plants structures, systems and components. Consequently, Korean and overseas nuclear industries have begun to consider the use of seismic isolation to increase safety, while using existing, and proven, plant designs and technologies.

Application of seismic isolation system to nuclear structures is generally recognized as an effective approach for significantly increasing seismic safety margins of nuclear facilities. Seismic isolation has the potential of significantly reducing overall design forces and in-structure response in the moderate to high frequency range compared to conventional fixed base designs. Since earthquake hazards in Korea are quite small, interest in seismic isolation of NPPs constructed in Korea is modest. However, construction of NPPs, like the Advanced Power Reactor (APR) 1400 Model NPP, in overseas countries where strong earthquakes are generated, suggests the need to assess the applicability of seismic isolation to achieve the necessary margin of safety.

There has been almost no nuclear facility in Korea where seismic isolation systems have been applied. However, isolation has been applied for some industrial facilities and infrastructures, such as LNG tanks and bridges. Seismic isolation techniques employed by the Korean nuclear industry have mainly been on research purposed reactors, such as next generation liquid metal reactors, rather than commercial NPPs. However, a series of research development projects have recently started for applying seismic isolation systems to the APR 1400, the standard model of Korean NPP.

APR1400 stands for Advanced Power Reactor with a 1,400 MW electrical power and pressurized water reactor developed in Korea. Four train direct vessel injection safety systems and fluidic devices in a safety injection tank are incorporated into the reactor, and a sixty year plant life is guaranteed. The reactor containment building is a pre-stressed concrete structure in the shape of a cylinder with a hemispherical dome, and is founded on a common basemat with the auxiliary building. The nuclear island structure consisting of the reactor containment building and the auxiliary building weighs 485,500 tons with overall plan dimensions of 103.6 m×102.4 m. The buildings and structures of the original fixed-base APR1400 plant have been designed based on a Safe Shutdown Earthquake (SSE) of 0.3 g as the Design Basis Earthquake (DBE). The seismic input motion enforced in the high frequency range is generated to envelope the design ground response spectrum of Reg. Guide 1.60.

2. KOREAN RESEARCH PROJECT

In 2011, a major project was initiated in Korea titled “Development and Application of Base Isolation System for Nuclear Power Plant Export.” The top tier objective of the five-year project is to develop essential technologies for the design of base-isolated NPPs [1]. The project is a cooperative activity including KEPCO Engineering and Construction Company (KEPCO E&C), Korea Hydro and Nuclear Power Company (KHNP), and the Korea Atomic Energy Research Institute (KAERI), along with a number of participating research organizations, universities, and consultants. The project is aimed at the practical application of base isolation to an existing standard plant that has been designed as a fixed-base facility for a DBE with a 0.30 g PGA. The use of base isolation is intended to increase the applicability of the standard design to sites with 0.50 g or greater peak ground accelerations. A preliminary schematic cross section through the plant is shown in Figure 1. Elastomeric and sliding bearings are being considered. The project is divided into four interrelated tasks. These tasks are:

1. to develop the essential technologies for the design of base-isolated NPPs such as bearing arrangement design, seismic analyses incorporating the bearing’s nonlinear dynamic behavior, and umbilicals (KEPCO E&C).
2. to develop design criteria for base-isolated NPP (KHNP).
3. to assess seismic performance of seismic isolation system for NPP (KAERI).
4. to develop domestic source of seismic isolators in Korea for use in NPPs (KHNP).

Nonlinear soil-structure interaction (SSI) analysis, seismic design of umbilicals, and the verification of the seismic design of base-isolated NPPs are newly studied in the design of base-isolated NPPs.

The frequency-domain analysis method is being investigated for a preliminary assessment of SSI effects on the response of base-isolated NPPs. The method, however, includes several limitations due to the simulation of material and geometric nonlinearities. Significant limitations of the equivalent linear method are found due to the stiffness of the bearings (i.e. the structural response), the nonlinear elastic vertical response, and the modelling of damping. However, Most of the limitations listed for the frequency-domain analysis do not exist in the nonlinear time-domain analysis. There are several material constitutive models and elements to account for nonlinearities of both soil and bearings. Practical engineering efforts are required with respect to the dimensioning of the soil domain mesh. The size of the elements must be determined considering frequencies of interest, the interaction with the response of the structure and the use of absorbing boundaries. This need for simulation of a relatively large region considerably increases the analysis time and renders time-domain analysis a computational intensive task. Hybrid methods combining frequency and time domain techniques are also considered as useful tools to solve SSI systems with structural non-linear behavior. However, most former hybrid methods have limitations based on the theories and practical application. Structural responses obtained from several hybrid methods used in the research are compared with results from time domain analysis [2].

In response to the large deformation of umbilicals such as interface piping system, the KEPCO E&C piping design department is extending their design procedures into dynamic nonlinear time history analysis. One of those development efforts is several ASME Boiler and Pressure Code action items that will have direct benefit for the base-isolated NPPs [3]. These activities are:

a) Incorporation of a Reversing Dynamic load criteria for Class 1 Piping in NB-3200
b) A Code Case with a strain based acceptance criteria for use with Appendix F
c) Update of Appendix F to provide detailed Class 2/3 design rules
d) A Code Case to allow Appendix XIII to be used for Class 2/3 design by analysis
e) An update to Appendix Y to implement the Reversing Dynamic Load criteria

There is a need for strict verification to ensure that isolation devices behave as expected, and that nonlinear dynamic analysis procedures can realistically predict the response of the bearings, the supported superstructure and its contents. Real-Time Hybrid Simulation experimental testing techniques provide a logical, efficient and economical method to assess the behavior of isolation bearings for different earthquake excitations and plant designs, and allow the effects of isolator nonlinearities, including the evolution of their properties with time, on the response of the isolators, structures, systems and components to be considered explicitly. Hybrid simulation may be particularly appropriate to assess the behavior of bearings under beyond design basis events. KEPCO E&C in collaboration with Pacific Earthquake Engineering Research Center is developing the processes of hybrid simulation as a method to validate the applicability of seismic isolation to NPPs and to obtain data necessary to confirm the practicality of nonlinear seismic analysis methods to predict the performance of isolation devices and of seismically isolated nuclear structures [4].

The Seismic Response Modification Device (SRMD) Test Facility of the University of California, San Diego (UCSD) was designed and used for real-time 6-DOF dynamic characterizations of full-scale seismic isolators and dampers using predefined loading protocols. The facility was originally developed jointly by the California Department of Transportation, the UCSD, and MTS Corporation of Eden Prairie, Minnesota. The SRMD test facility at UCSD is adapted as part of this project to conduct hybrid simulation. The hybrid simulation architecture for the SRMD includes a computational driver, the SRMD control system and a real-time Digital Signal Processor to communicate between the digital computers and the analog input/outputs of the SRMD control system. They were newly installed for this research project in 2014.

UNISON manufacturing lead plug rubber bearings (LPRB) and ESCO RTS manufacturing EradiQuake System (EQS) bearings performed quality control tests on the test specimen. LPRB used for prototype testing were 1,500 mm in diameter and had a 320-mm diameter lead core, see Figure 2. Thirty-two rubber layers with a 7-mm thickness resulted in a total rubber thickness of 224 mm. These were sandwiched between 31 steel plates also with 7-mm thickness and 60-mm thick end plates giving the bearing a total height of 527 mm. Failure tests were performed in order to characterize the behavior of the LPRB for beyond design level response through an ellipsoidal input motion up to 500% shear strain in the bearing. The bearing failed at approximately 1092 mm longitudinal displacement. The peak longitudinal shear strain was therefore 488% at failure, a factor of 4.9 times the design shear strain. ESCO RTS provided EQS isolators with two-MER springs, which combine a flat slider with a restoring force generated by horizontal compression springs, see Figure 3. The isolators had a low profile, 474 mm. The plan dimensions were 2,110 mm by 2,135 mm. As part of the characterization tests on the EQS bearing, square orbit input motions were applied at different axial loads. For the low axial load case (178 kN), the interior block, to which all of the springs are attached, started to rotate around the vertical axis of the bearing. This occurred during the last cycle at a displacement of 120 mm corresponding to the design displacement. It was confirmed that hybrid simulation is indeed a viable testing method to experimentally assess the behavior of large isolators at full-scale. Tracking performance in terms of delays was significantly improved by installing a feedforward-control software patch. Final testing speeds increased from 25-times slower than real-time to five times slower than real-time for the friction type bearing tests.

KEPCO E&C is extending hybrid simulation into the form of international joint research program at IAEA ISSC EBP phase 2. This program was allocated to task 2.3 Hybrid simulation of seismic isolation. The program will include blind analyses made by the participants (benchmarks), workshops, and hybrid simulation tests [5].

KAERI has been in parallel developing the performance criteria of seismic isolation systems and umbilicals of base isolated NPPs. Based on the target performance goal provided in ANSI/ANS 2.26, the performance criteria for base isolated NPPs are being developed in this research. KAERI's research on such performance criteria deals the following topics: defining performance goal of NPP, generation of the input ground motions for performance evaluations, numerical NPP models with base isolation systems, the ultimate capacity of base isolation systems, a performance evaluation of base isolated structures, performance tests and long-term behavior of the bearings, a seismic fragility assessment for the seismic isolation system and umbilicals, and a seismic risk assessment for base isolated NPPs. The safety of the base isolation system needs to be secured with high confidence because there is no redundant component for it. However, the behavior and failure limit of the bearings may not be easily predictable because of the high nonlinearity and earthquake loading dependent characteristics. Therefore, a variety of characteristic tests were conducted for seismic isolation devices to specify the performance criteria of seismic isolation systems. The ISO standard specimens, 1/3 scale models, and real-scale LPRB models were tested for an evaluation of the characteristic behavior. The ultimate capacity of bearings depends on the shear strain levels, strain rates, input motions, and bi-directional effects. Aging characteristics of the bearings were also investigated. For the seismic safety evaluation of umbilicals, a critical equipment system is chosen, and seismic risk impacts are analyzed in view of deformation increase by the installation of bearings. To validate the numerical piping system model and defining failure mode and limit states, quasi-static loading tests were conducted on the scale-modelled piping components before the analysis procedures were undertaken. A fragility analysis was conducted using the results of an inelastic seismic response analysis. Finally, the performance criteria will be verified through a seismic risk assessment of base-isolated NPPs.

3. CONCLUSIONS

The Korean seismic isolation research project is being performed to increase the seismic safety and enhance the standardization of Korean generation III nuclear power plants. Also, the Korean research team including KEPCO E&C would like to contribute to establishing the international standards for base-isolated NPPs or facilities through participating in the various international programs.

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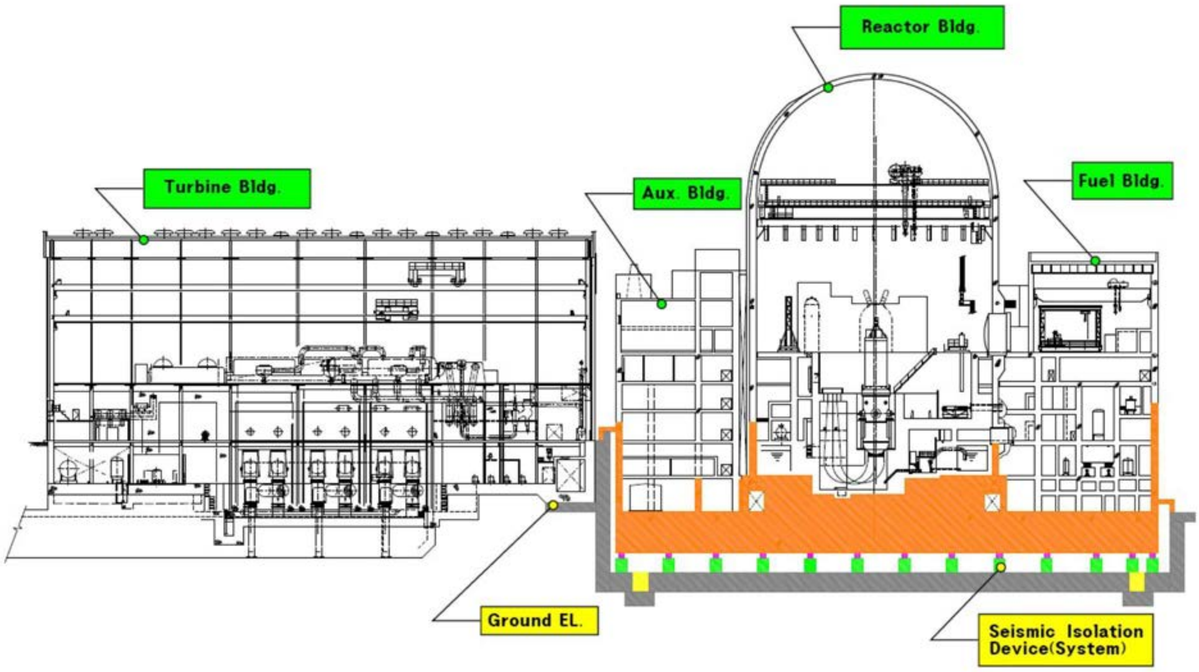


Figure 1. Cross section showing the isolation system installed under a Korean APR 1400 standard plant design.

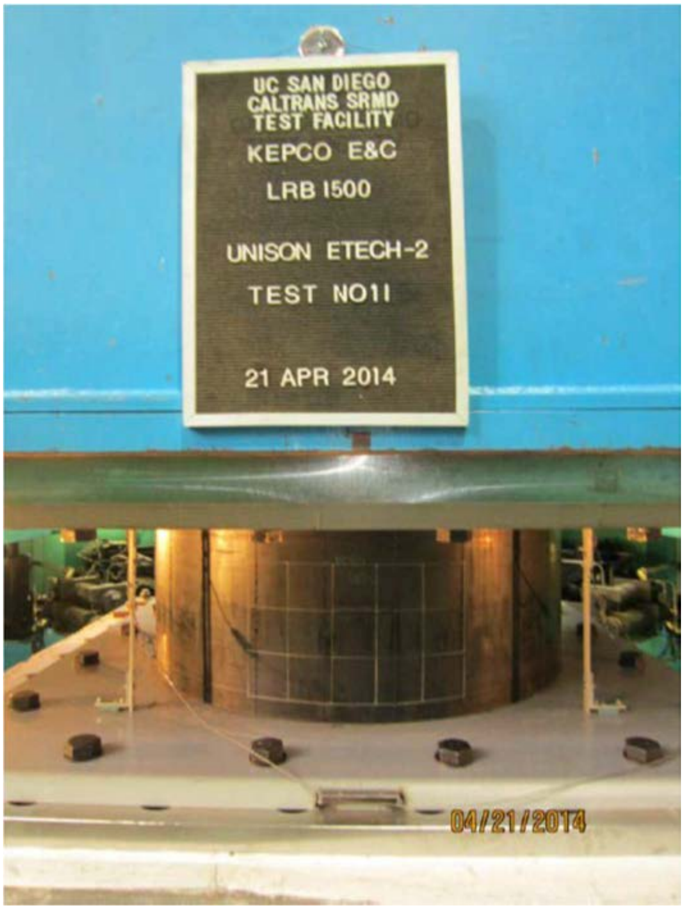


Figure 2. LPRB manufactured by UNISON to be used for prototype tests


Figure 3. EQS bearing manufactured by ESCO RTS to be used for prototype tests

IV-4. REPORT FROM JAPAN

I. INTRODUCTION

BACKGROUND, NECESSITY AND PURPOSE OF ESTABLISHING THE TECHNICAL REVIEW GUIDELINES FOR STRUCTURES WITH SEISMIC ISOLATION

Seismic isolation technology can be broadly classified into building isolation and equipment isolation, both of which have been extensively studied by the nuclear field such as the former Japan Atomic Energy Research Institute, nuclear industry and universities and also by the non-nuclear field for more than a few decades. Consequently, owing to results of research accomplishments and construction experiences, seismic isolation technology has earned recognition as a mature technology. On the basis of such accomplishments, the Regulatory Guide for Reviewing Seismic Design was revised (in September, 2006). In this Guide, requirement for enhancing the condition of design basis ground motion and recognition of the seismic isolation technology were included. Furthermore, existence of the remaining risk was recognized and the mentioning of the rigid structure in the former Review Guide for Seismic Design was eliminated. Thus, the possibility for application of the seismic isolated structures had further increased.

The Niigataken Chuetsu-Oki Earthquake (in July, 2007) occurred in the vicinity of Kashiwazaki-Kariwa Nuclear Power Station and the ground motion 2.5 times as big as the design seismic response was observed during the earthquake. The door of the emergency response room failed to open, which seriously hindered the post-earthquake activities. Based on the lessons learned from this earthquake, the licensees have been actively promoting to establish the seismically isolated emergency administrative buildings in their sites in order to successfully carry out post-earthquake activities. Some of the examples include the seismic isolated administrative buildings built in Kashiwazaki-Kariwa Nuclear Power Station and Fukushima Daiichi and Daini Nuclear Power Stations.

In the off the Great East Japan Earthquake (in March, 2011), tsunami struck Fukushima Daiichi Nuclear Power Station and caused the loss of reactor cooling function, leading to the release of radioactive materials from the containment vessel beyond the site boundary. Emergency response activities at Fukushima Daiichi and Daini Nuclear Power Stations were directed at the above-mentioned seismic isolated administrative building, which was effectively utilized even under the situation affected by the main quake and after quakes. Based on these experiences, application for construction of seismically isolated facilities important to safety including administrative building is expected.

On the other hand, there has been a growing trend toward constructing new nuclear power plants in the world. The possibility of adopting seismic isolation technology is increasing for the purpose of standardizing the seismic design, not only in high seismicity countries but also in moderate or low seismicity countries.

The Japan Nuclear Energy Safety Organization (JNES) took over the research achievements on the seismic isolation technology made by the above-mentioned former Japan Atomic Energy Research Institute in October, 2003, and has been formulating the design principle of the seismic isolated structures, and assessing the reduction of remaining risk in case where seismic isolation systems are implemented in the components important for seismic safety. JNES has provided the results of these researches to the International Atomic Energy Agency (IAEA) and the U.S. Nuclear Regulatory Commission and supports the preparation of the IAEA's seismic isolation standards. Having these as a background, JNES established The Seismic Isolation Standard Subcommittee in FY2009 under The Seismic SSCs Standard Committee, consisting of external experts. The subcommittee collected and examined the opinions on the review guidelines for the seismic isolation structures and incorporated them into JNES's draft Technical Review Guidelines for Structures with Seismic Isolation, and then prepared the final edition.

POLICY FOR ESTABLISHING THE TECHNICAL REVIEW GUIDELINES FOR STRUCTURES WITH SEISMIC ISOLATION

The policy for establishing the Technical Review Guidelines for Structures with Seismic Isolation was to enable the guidelines to be utilized not only in Japan but also in foreign countries. Specifically, the guidelines cover the entire plant life from the design stage to the decommissioning stage, and can be applied to the respective sites with high, moderate and low seismicity. In addition, both newly established reactors and existing reactors are subject to the guidelines. Also, both of the building isolation and equipment isolation including seismic floor isolation are included in the scope of application of the guidelines, and both horizontal and vertical ground motions are considered. Further, the guidelines provide as many examples and explanations as possible.

II. TECHNICAL REVIEW GUIDELINES

1 . SCOPE

The Guidelines set forth herein shall be used for the evaluation of seismic isolated power reactor facilities.

However, the Guidelines may also be used, as a source of useful information, for the evaluation of other types of nuclear installations that employ a seismic isolation design. Note that nonconformity to the Guidelines shall not be a cause of rejection if it is justifiable by a good reason.

(Commentary)

- *The Guidelines set forth herein are used by JNES when it examines seismic isolation structures implemented at power reactor facilities in response to applications for approval submitted by utilities.*

2. BASIC POLICY

2.1 Preconditions

2.1.1 Scope

- The stages addressed by the Guidelines shall be seismic design, risk assessment, construction and operation.
- The Guidelines may be applied in regions of high, moderate and low seismicity.

2.1.2 Target Facilities

- At newly constructed reactor facilities, the Guidelines shall address buildings and equipment for the reactors of ongoing or next-generation type.
- At existing reactor facilities, the Guidelines shall address equipment.
- Existing reactor facilities for which retrofitting is possible shall not be reject.

2.1.3 Target Types of Seismic Isolation Structure and the Directions of Seismic Isolation

- The type of seismic isolation structure is building isolation or equipment isolation. Any seismic isolation structure that combines building isolation and equipment isolation is allowable.
- The available directions of seismic isolation are the following: only in the horizontal direction, or only in the vertical direction, or in both the horizontal and vertical directions.

(Commentary)

- *Assuming that tasks such as the development of seismic isolation devices and the verification of its reliability, as well as the development of design methodology and the verification of its validity, are properly attended to by utilities and other organizations, the type of seismic isolation equipment to be used or the design methodology to be employed are out of scope of the Guidelines, and the Guidelines give attention mostly to requirements concerning the implementation of a base- isolated structure at nuclear power facilities.*

2.1.4 Relationship between the Seismic Isolation Function and Seismicity

- Seismic isolation may serve the two following major functions:
  (i) Enhancing seismic safety by reducing acceleration response to ground motion, while trying not to cause excessive increase of displacement response.
  (ii) Maintaining the responses of equipment in the base-isolated structures at a similar level regardless of different ground condition, and standardizing seismic design of equipment.
  - In the implementation of the seismic isolation structure, the intended purpose of the seismic isolation is related generally with the seismicity described in 2.1.1 above. When implemented in a region of high seismicity, the main purpose meets (i) in the above paragraph. When implemented in a region of low seismicity, the main purpose meets (ii) in the above paragraph. When implemented in a region of moderate seismicity, it is expected that the seismic isolation would serve both function, (i) and (ii).

2.1.5 Determination of the Allowable Displacement Limit of the Seismic Isolation Device

- The allowable displacement limit of the seismic isolation device may be determined using either one of the following two methods:
  (i) Determination based on ultimate displacement of the seismic isolation device such as rubber bearing.
  (ii) Determination based on satisfaction of the performance goal for core damage frequency obtained from the risk assessment.

(Commentary)

- *The allowable displacement limit of the seismic isolation device may be determined using either of the following methods:*

(i) Determination based on ultimate displacement of the seismic isolation device or crossover piping installed between seismic isolated building/equipment and non-isolated building/equipment.

(ii) Determination based on satisfaction of the performance goals for core damage frequency and containment failure frequency evaluated by the risk assessment.

In the past, the first method (i) has been used normally in the designing of seismic isolation structure. However, it is also possible to use the second method (ii) because, when a seismic isolation structure is applied, the response displacement of the seismic isolation device could be a virtual main cause of damages.

Specifically, the methodology of seismic PSA can be used in the second method (ii).

2.1.6 Input Ground Motion for the Base-Isolated Structure

- As a general rule, input ground motion for the response analysis of the base-isolated structure shall be obtained from earthquake transmission analysis utilizing the design basis ground motion.
- The design basis ground motion is required to contain low frequency components. In terms of the earthquake transmission analysis, the filtering effect for those components should be checked.

(Commentary)

- *As a general rule, input ground motion for the response analysis of the base-isolated structure shall be obtained from earthquake transmission analysis utilizing the design basis ground motion.*
- *Considering that base-isolated structure has relatively low natural frequency, the design basis ground motion is required to contain low frequency components. In terms of the earthquake transmission analysis, the reviewer should check the filtering effect for those components not to reduce conservativeness of design condition.*

2.1.7 Method of Seismic Response Analysis of Base-Isolated Structure

- As a general rule, seismic response analysis of base-isolated structures shall be conducted using the time history analysis.

2.2 Basic Policy Concerning the Implementation of Seismic Isolation Structure

- Base-Isolated structures shall be as seismically safe and reliable as aseismic structures.
- Base-isolated structures shall be designed to comply with provisions in the New Regulatory Requirements for Light Water Nuclear Power Plants (hereinafter “New Rules”), as a general rule.
- Base-isolated structures have a long natural period and therefore differ from aseismic nuclear facilities in their characteristics of response to ground motion. If using design methods different from those described in the Seismic Guide is adequate to reflect those characteristics in design, design methods may be changed in case where the reason for doing that is clearly stated.
- If the design method based on the New Rules is likely to compound the risk of seismic isolated facilities, an appropriate design policy should be introduced

(Commentary)

- *When a seismic isolation structure is implemented, the natural period of the superstructure is longer than that of aseismic structures. Apart from that, however, the* *philosophy of seismic design does not differ much between seismic isolation structures and aseismic structures.*

- *Therefore, seismic isolation structures shall also be designed to comply with provisions in the New Regulatory Requirements for Light Water Nuclear Power Plants established by Nuclear Regulation Authority (NRA), as a general rule.*
- *Since the basic aim of the seismic isolation structure is to reduce dynamic energy of earthquake by the seismic isolation device, the seismic safety of seismic isolation structure depends on its dynamic behavior during earthquake. Therefore, a sufficient safety margin shall be provided when defining the design basis ground motion and when designing the seismic isolation equipment, for example.*
  Moreover, effort must be made to make the residual risk as small as practicable.

3. REVIEW ON SEISMIC DESIGN STAGE

3.1 Classification of Seismic Importance

- The seismic classification of seismic isolation device shall be categorized in the same class of the superstructure. In addition, the following definition shall apply:
  -- Building isolation
  The seismic isolation device shall be regarded as an indirect support structure.
  -- Equipment isolation
  The seismic isolation device shall be regarded as a direct support structure (in the category of "other support structures") for the supported components.
- It is necessary to consider a possibility that damage of low classification facilities would affect high classification facilities.

(Commentary)

(1) Building isolation case

- *In the case of building isolation, the seismic isolation device, positioned between the superstructure and substructure, has a function to support the building.*
- *In this case, the seismic isolation device falls into the category of "indirect support structure" according to the Technical Code for Seismic Design of Nuclear Power Plants (JEAC4601-2008): "structure made of reinforced concrete, steel frame or the like bearing the load transmitted from direct support structure."*
- *The seismic isolation device, therefore, shall be regarded as an indirect support structure.*

(2) Equipment isolation case

- *Seismic isolation device shall be fall into same classification of seismic importance with the isolated equipment, and it shall be regarded as a direct support structure for the superstructure (other support structures).*

3.2 Design Basis Ground Motion

- The design basis ground motion used in the design of the base-isolated structure (hereinafter "input ground motion") must be determined appropriately in consideration of differences of seismicity (high, moderate or low) around the site and differences of horizontal and vertical ground motions.
- As a general rule, input ground motion shall be obtained from earthquake transmission analysis utilizing the design basis ground motion.

3.2.1 Differences of Seismicity

1) High Seismicity Region

Even though the design basis ground motion Ss as defined in the New Rules may be applicable, sufficient consideration to use the conventional Ss, which is for non-isolated structure, is needed because a seismic isolation structure generally has a relatively long natural period. Therefore, its validity as the design basis ground motion for a seismic isolation structure shall be checked with attention to the points described in the section (2), and the design basis ground motion must be newly created if necessary.

2) Moderate Seismicity Region

The same instruction as above [1) High Seismicity Region] shall apply.

Considering the medium level of seismicity, two or more sites may share the same design basis ground motion.

In that case, the shared design basis ground motion shall be conservative enough to be able to serve as a representative design basis ground motion applicable to multiple sites.

3) Low Seismicity Region

The same instruction as above [2) Moderate Seismicity Region] shall apply.

Considering the low level of seismicity, it shall be allowed to prepare and use an internationally agreed design basis ground motion.

3.2.2 Differences of Directions of Ground Motions

The following provisions concerning differences of horizontal and vertical ground motions shall apply to all three cases described above that address differences of seismicity.

1) Horizontal Ground Motion

Considering that a seismic isolation structure has a relatively long natural period (usually between 2.0s and 5.0s), proper attention must be given to longer period components in the design basis ground motion.

(Commentary)

- *The design basis ground motion Ss shall be defined in pursuant to provisions in the New Rules, in consideration of both ground motions with specified source (ground motions derived from fault models and response spectrum) and ground motions with no specified source.*
- *Considering that the seismic isolation structure has a relatively long natural period (usually between 2.0s and 5.0s), the design basis ground motion must sufficiently include longer period components that is required in the design of the seismic isolation structure.*

  In the determination of the design basis ground motion, it is similarly important to give attention to the possibility of a great earthquake at a distant location, which is going to induce longer period vibration.
- *Considering that the seismic isolation structure has a relatively long natural period, the design basis ground motion shall have sufficient duration time.*
- *In the determination of the design basis ground motion Ss, attention must be given to factors that may influence long period components of the ground motion: active faults near the site, distant earthquake, deep soil structure affecting the propagation route characteristics, etc.*

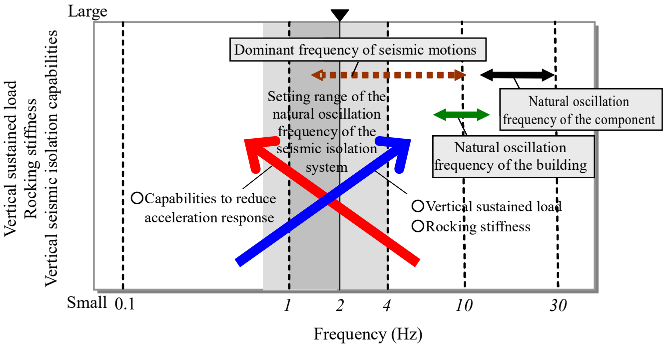
- *If observation records of ground motions with long period components are available, it is advisable to use such records to supplement the design basis ground motion determined by the procedure described above.*

2) Vertical Ground Motion

When the vertical seismic isolation is installed, the natural period in the vertical direction usually ranges from 0.5s to 1.5s. In that case, it is possible to use the design basis ground motion defined in the New Rules. If the vertical natural period largely exceeds 1.5s due to the configuration of the seismic isolation device, for example, it is necessary to reevaluate, like in the case of 1) above, giving attention to the longer natural period.

(Commentary)

- *Seismic isolation in the vertical direction differs from that in the horizontal direction because of the necessity to support the dead weight. This gives rise to the following characteristics: (i) An excessively long natural period in the vertical direction causes difficulty in supporting the dead weight; (ii) It may also make the structure more prone to rocking motion. Therefore, the natural period in the vertical direction is usually designed to range approximately between 0.5s and 1.5s. In the case of vertical seismic isolation, attention should be paid to the fact that available period range is limited.*
- *Resonance of the base-isolated structure shall be investigated because vertical ground motions whose dominant period components were included in period range above were observed.*
- *In the case where the vertical natural period of the base-isolated structure is relatively long (largely exceeds 1.5s), attention should be paid to supporting function of the superstructure.*
- *In the case where the vertical natural period is shorter than 0.5s, attention should be paid to decrease of isolation effect.*
- *Vertical natural period of the base-isolated structure is limited between 0.5s and 1.5s. Since vertical ground motion whose dominant period components were included in this range was observed at Taiwan Chi-Chi Earthquake, attention shall be paid to the resonance of the superstructure. However, response acceleration due to the resonance could be suppressed by countermeasures such as increase of damping factor and so on.*
- *Basic concept to be considered when deciding natural frequency of the vertical seismic isolation described above is shown in the figure.*



Conditions for deciding natural frequency of the vertical seismic isolation

3.3 Basic Performance Requirements for Seismic Isolation Device

The seismic isolation device shall be capable of supporting, restoring and damping, and shall stably maintain these functions at a satisfactory level throughout the in-service period. In the case where a stopper is installed into the seismic isolation device, the stopper shall not affect the function of the seismic isolation device. The evaluation of these functions differs according to regional differences of seismicity (classified as high, moderate and low).

3.3.1 High Seismicity Region

1) Supporting Function

- The seismic isolation device shall be capable of stably supporting the superstructure in the presence of vertical load (in normal state, during earthquake and after earthquake). The quantity of relative displacement in the vertical direction shall not differ significantly among the dead weight supporting devices.
- The seismic isolation device shall be capable of stably supporting the superstructure in spite of changes in the axial force due to the horizontal deformation during earthquake.

(Commentary)

Seismic isolation devices that concern the supporting function fall into two major groups: laminated rubber bearings and rolling/sliding bearings.

As a general rule, the seismic isolation device shall use only those which have gained the approval of the Minister of Land, Infrastructure, Transport and Tourism on seismic isolation materials.

2) Restoring Function

- The seismic isolation device shall be able to exert a restoring force against the design seismic force derived from the design basis ground motion with adequate safety margin.
- The seismic isolation device shall tolerate deformation, with sufficient safety margin, up to the allowable displacement limit.

The allowable displacement limit of the seismic isolation device may be determined using either one of the following two methods:

(i) Determination from the ultimate displacement of the seismic isolation device or the crossover piping that connects between base-isolated building/equipment and non-isolated building/equipment.

(ii) Determination from the viewpoint of satisfying performance goals for core damage frequency and containment failure frequency based on the risk assessment.

(Commentary)

(1) Basic performance requirements

Seismic isolation devices that concern the restoring function fall into two major groups: laminated rubber bearings and springs.

(2) Determination of the Allowable Displacement Limit

The first method (i) has been used normally in the design of seismic isolation structure. However, it is also possible to use the second method (ii) because, when a seismic isolation structure is applied, the excessive displacement of the seismic isolation device is virtually the dominant cause of damages. Specifically, the methodology of seismic PSA can be used to implement the second method (ii).

3) Damping Function

- The seismic isolation device shall have sufficient damping capability corresponding to the characteristics of the device.

(Commentary)

Seismic isolation devices that concern the damping function fall into three major groups: hysteretic dampers, fluid dampers and friction dampers.

4) Stopper Function

- There shall be enough clearance between the seismic isolation device and the excessive displacement stopper so that the function of the seismic isolation device would be kept.

3.3.2 Moderate Seismicity Region

The basic performance requirements for seismic isolation device implemented in a moderate seismicity region shall be similar to the requirements described above for "3.3.1 High Seismicity Region"

3.3.3 Low Seismicity Region

The basic performance requirements for seismic isolation device implemented in a low seismicity region shall be similar to the requirements described above for "3.3.1 High Seismicity Region"

3.4 Design Policy of Base-Isolated Structure

In the design of the base-isolated structures, it is possible, as a general rule, to make use of conventional design methods for non-isolated structures such as those described in the Technical Code for Seismic Design of Nuclear Power Plants (JEAC4601-2008).

However, base-isolated structures differ from non-isolated structures in vibration characteristics because they have a relatively longer natural period. The design methods for seismic isolation structures must take into account such differences. This section describes design policy considerations unique to base-isolated structures.

(Commentary)

- *When evaluating the structural integrity of base-isolated structure against earthquakes, estimating cause of failure and critical parts related to the failure shall be conducted, and appropriate methods for strength assessment and function maintainability assessment shall be chosen.*
- *Since the response characteristics of base-isolated structure depends on the configuration of seismic isolation device, the topics requiring consideration shall be evaluated by type of the seismic isolation device which is installed to the seismic isolation structure.*

3.4.1 Input Ground Motion

- In the case of building isolation, the input wave obtained from earthquake transmission analysis utilizing the design basis ground motion is a ground motion at the base mat of the substructure. Appropriate analysis method should be selected considering structure and property of the soil in which the earthquake transmits. In the case of equipment isolation inside a building, seismic response analysis of building is conducted to obtain the response of substructure or the floor on which the equipment isolation is installed and take the response wave by the analysis as the input wave to the equipment isolation. In the case of outdoor equipment isolation, seismic response analysis of soil is conducted to obtain the response of the substructure and take the response wave by the analysis as the input wave to the equipment isolation.

3.4.2 Evaluation of the Basic Performance of Seismic Isolation Device

The seismic isolation device shall stably maintain the required functions (supporting, restoring and damping functions) at a satisfactory level throughout the in-service period. See Section 5.3 for detailed discussions on this subject.

3.4.3 Design Basis Seismic Force

- The dynamic seismic force defined in the New Rules shall be referred to in the design of base-isolated structure.
- In the calculation of the dynamic seismic force, the designer shall use an appropriate ground motion according to seismic classification of structure/component, and it shall be based on the design basis ground motion Ss or another ground motion. (See Section 3.2.)
- In the determination of the design basis seismic force, it shall be ensured that the seismic force corresponding to dominant natural period band of the base-isolated structure is not lower than that for base-isolated structures implemented in non-nuclear facilities.

3.4.4 Seismic Response Analysis Method

- As a general rule, the seismic response analysis of base-isolated structures shall be conducted using the time history analysis. A different method of seismic response analysis can be used, provided that its validity is demonstrated.

3.4.5 Seismic Response Analysis Model

- It is necessary to use an appropriate seismic response analysis model that properly simulates the vibration characteristics of the seismic isolation device.

3.4.6 Seismic Isolation Element Characteristics for Seismic Response Analysis

- The characteristic values of the seismic isolation element for seismic response analysis must be determined in consideration of the service environment, etc.
- Upon the completion of seismic isolation elements for actual implementation, the characteristics such as stiffness and damping factor shall be evaluated by testing all products, as a general rule, in order to confirm the validity of the seismic isolation element characteristics used in seismic response analysis.
  The above provision shall not apply if testing up to the design condition may cause change of design property (e.g. plasticity of steel bar damper). In that case, the validity of the seismic isolation element characteristic values used in seismic response analysis can be confirmed by feasible testing and combining the test result with analysis, etc.

A similar adjustment is allowed when testing is difficult for certain seismic isolation element due to their large size. If total inspection for the elements is deemed unnecessary because the dispersion of seismic isolation element characteristic values among products is evidently so small that it cannot affect the result of seismic response analysis of seismic isolation structure, it can be substituted by sampling inspection, provided that its validity is demonstrated.

(Commentary)

- *The determination of seismic isolation element characteristics for seismic response analysis requires the consideration of service conditions, taking note that seismic isolation elements would be placed under severe condition in the case of equipment isolation.*

- *When the seismic isolation device is designed, the actual characteristics (spring stiffness and damping ratio, for example) of them have not been confirmed. Therefore, upon the completion of seismic isolation elements for actual implementation, all of them, as a general rule, shall be subjected to product testing for the determination of characteristic values, which should be compared with design values for the purpose of demonstrating the validity of design.*

  If total inspection for the elements is deemed unnecessary because the dispersion of seismic isolation element characteristic values among products is evidently so small that it cannot affect the result of seismic response analysis of seismic isolation structure, it can be substituted by sampling inspection, provided that its validity is demonstrated.
- *Judging validity of seismic isolation element characteristics for design depends on whether or not the differences between the assumed and measured values are so small that they do not affect seismic isolation functions.*
- *If the differences between the two above are so large that they may affect designed performance of the seismic isolation structure, seismic response analysis shall be newly conducted using the measured values of seismic isolation elements in order to confirm the availability of required seismic isolation functions.*
- *Depending on the type of seismic isolation elements, testing of the actual product up to the design condition may be difficult. (For example, testing a steel rod damper under the design seismic load is going to cause plastic deformation.) Moreover, the building isolation may involve the use of 1,000 ton-class laminated rubber bearings, which may be too large to be tested, or at least the testing of all of them may be difficult.*

  In that case, the validity of the seismic isolation element characteristics used in seismic response analysis can be confirmed by combining practicable test with different specimens and analysis.

3.4.7 Combination of Horizontal and Vertical Seismic Loads

- The combination of horizontal and vertical seismic loads shall be addressed by an appropriate method in consideration of the characteristics of the seismic isolation structure.
- Coupling behavior of vertical seismic force caused by rocking motion due to horizontal ground motion and vertical ground motion should be considered.

(Commentary)

- *The combination of horizontal and vertical seismic loads shall be addressed by an appropriate method in consideration of the characteristics of the seismic isolation structure.*
- *In the case of horizontal seismic isolation, the base-isolated structure has a relatively long natural period in the horizontal direction while a vertical natural period is short, and therefore maximum responses in horizontal and vertical directions are likely to take place simultaneously.*
- *When addressing the combination of horizontal and vertical seismic loads in the design of seismic isolation structures, the use of the Square Root of Sum of Squires (SRSS) method as in the design of non-isolated structures may result in non-conservative estimations (i.e. lesser safety margin).*
- *Therefore, an appropriate method, such as taking the sum of absolute values, taking the algebraic sum of the time history of seismic load in the horizontal and vertical*

directions, and horizontal/vertical simultaneous input analysis, shall be chosen in consideration of the characteristics of the seismic isolation structure.

- *It is necessary to evaluate whether the coupling behavior of vertical seismic force caused by rocking motion due to horizontal ground motion and vertical ground motion would take place.*
- *A combination method like SRSS may be used neglecting the coupling behavior mentioned above if it is well justified by a reason such as that peaks do not overlap or synchronize between horizontal and vertical ground motions.*
- *Depending on the configuration of seismic isolation elements, it will be necessary to consider the combination of seismic loads in two horizontal directions. The combination of seismic loads in two horizontal directions requires similar considerations described above.*

3.4.8 Other Considerations

The following describes other topics that require consideration.

- There is a wide variety of seismic isolation devices and the topics requiring consideration depends on the configuration of the device. In designing a seismic isolation structure, therefore, topics requiring consideration have to be determined for every seismic isolation device.
- In the case of design of excessive displacement stopper and dustproof cover, influences on the seismic isolation function should be considered.

(Considerations common to building isolation and equipment isolation)

1) Eccentricity of the center of rigidity and the center of gravity

- A large distance between the center of rigidity and the center of gravity leads to a rotational movement during earthquake, which may cause inconveniencies such as the increase of relative displacement during earthquake. Therefore, care must be taken to make its center of rigidity and its center of gravity positioned as close together as possible.
- If there is a large distance between the center of rigidity and the center of gravity, it shall be ensured that the seismic isolation device is able to provide the required seismic isolation functions. Hereinafter, “the required seismic isolation functions” mean the functions described in Section 2.2 “Basic Policy Concerning the Implementation of Seismic Isolation Structure”.

2) Consideration of rocking motion during earthquake

- The seismic isolation device shall be able to provide the required seismic isolation functions even in the presence of rocking motion.

3) Consideration of variation in the performance of seismic isolation device

3-1) Dispersion of seismic isolation element characteristics

- The seismic isolation device shall be able to provide the required seismic isolation functions even in the presence of dispersion of characteristics of seismic isolation elements (rigid elements, damper elements, etc.), including other influences such as aging, temperature changes and so on.

(Commentary)

- *The seismic isolation device is composed of rubber elements, spring elements, damper elements, etc. There is usually dispersion in the characteristics (spring stiffness, damping ratio, etc.) of these elements. Therefore, it shall be ensured in* *design that the seismic isolation device is able to provide the required seismic isolation functions in spite of dispersion of characteristics.*

3-2) Changes of seismic isolation functions during earthquake

- The seismic isolation device shall be able to provide the required seismic isolation functions even though the characteristics of seismic isolation elements go through changes while the seismic isolation structure moves during earthquake.

(Commentary)

- *It is necessary to identify the factors that cause changes of the characteristics of seismic isolation elements during earthquake and estimate the magnitude of changes, and to ensure that the seismic isolation device is able to provide the required seismic isolation functions in spite of such changes.*
- *Factors that cause changes to the characteristics of seismic isolation elements depend on the configuration of elements. The causes shall be identified and measures shall be taken considering the configuration of the seismic isolation elements.*

3-3) Changes in seismic isolation functions due to external events other than earthquakes

- When implementing the seismic isolation structure, it is also important to ensure protection against external events other than earthquakes by taking measures as required.

4) Seismic safety of facilities unique to seismic isolation structure

- As a result of implementing the seismic isolation structure, seismic risks of certain facilities may increase. Such facilities shall be clearly identified and it shall be demonstrated that they still retain seismic safety.

The followings are examples of such facilities:

-- Crossover piping, etc., components installed between building/equipment and non-isolated building/equipment (See Section 3.5)

-- Facilities in which sloshing shall be taken into account

(Considerations for building isolation)

1) Seismic safety of structures unique to building isolation

- The structures unique to building isolation (pedestal, etc.) shall be as safe as the rest of the base-isolated structure.
- The surrounding wall which is constructed between the building and surrounding soil shall be designed in such a manner that its collapsing does not affect the function of seismic isolation structure.

(Considerations for equipment isolation)

1) Variation of seismic isolation characteristics depending on the direction of seismic load input

- The seismic isolation device shall be able to provide the required seismic isolation functions irrespective of the direction of seismic load input.

(Commentary)

- *A certain kind of seismic isolation device may show different characteristics (e.g. stiffness) depending on the direction of seismic load input.*
- *In the case of spring-damper elements that can be used for equipment isolation, the stiffness in the parallel direction to element installation differs from the stiffness in*

the diagonal direction. As a result, the seismic isolation functions vary with the direction of seismic load input.

- *Therefore, it shall be ensured that such seismic isolation elements provide the required seismic isolation functions irrespective of the direction of seismic load input.*
- *Certain damper elements have also directional properties. When such damper elements are used, care must be taken to minimize the directional variation of seismic isolation characteristics.*

2) Response characteristics depending on the configuration of the seismic isolation device

- Some kinds of seismic isolation devices have vibration characteristics of inducing nonlinear seismic response. The seismic isolation device shall be able to provide the required seismic isolation functions irrespective of kind of device.

(Commentary)

- *A certain kind of seismic isolation device may show some irregular behaviors (e.g. nonlinear behavior during earthquake caused by friction elements used as trigger or damper).*
- *Therefore, when implementing a seismic isolation structure, attention shall be given to the characteristics of the seismic isolation device and it shall be ensured that the seismic isolation structure maintains the required functions in spite of such irregular behaviors.*

3.5 Interfaces between Base-Isolated Structure and Non-Isolated Structure

Compared with non-isolated structures, base-isolated structures respond to earthquake with greater displacements and therefore require the following considerations concerning the design of the interface between the base-isolated and non-isolated structures.

3.5.1 Influences on Seismic Isolation Functions

- Piping, cables, floor and similar installations that connect between base-isolated and non-isolated building/equipment shall not have any significant influences on the seismic isolation functions of the seismic isolation structure.
- It shall be ensured that the base-isolated structure will not collide with other structure during earthquake.

(Commentary)

- *Remembering that the base-isolated structure is displaced not only into a direction parallel to its edges but also into a diagonal direction during earthquake, it shall be ensured that there is a sufficiently large clearance between base-isolated and non-isolated structures, and also that there is no other structures within the range of motion of the base-isolated structure.*
- *It shall be ensured that there is no risk of a crossover piping or floor adversely affecting the seismic isolation functions.*
- *For example, concentrated installation of the crossover component would cause torsional motion of the base-isolated structure, and it is also possible that frictions due to the crossover component would constrain the motion of the base-isolated structure.*

3.5.2 Maintaining the Integrity of Crossover Components Against Earthquake

- Crossover piping, etc. shall maintain their integrity against displacement caused by earthquake.

(Commentary)

- *Examples of crossover components between base-isolated and non-isolated building/equipment include piping, cable trays, air conditioner ducts and power cable conduit pipes and so on. All these components must maintain their integrity against displacement caused by earthquake.*
- *Methods that can be employed to cope with displacement include the strategic routing of piping and the use of expansion joints, etc. A choice is made by utility.*
  Any method other than the above for coping with displacement can be allowed provided that its validity is demonstrated.

3.6 Load Combination and Allowable Limits

3.6.1 Combination of Loads

Seismic load and other loads shall be appropriately combined according to provisions in the New Rules.

If there is any load that arises due to the implementation of a seismic isolation structure, it shall be considered as required when combining loads.

(Commentary)

- *In the designing of seismic isolation structures, the combination of loads is in a similar manner as it has been considered in the designing of non-isolated power reactor facilities. The compliance with the New Rules is required.*
- *That is to say, the utility is expected to consider the combination of seismic load and other loads according to the ongoing practices (established for the designing of non-isolated power reactor facilities).*
- *If there is any load that arises specifically due to the implementation of seismic isolation (e.g. additional load at the time of replacement of seismic isolation devices), it shall be properly taken into account.*

3.6.2 Allowable Limit for Seismic Isolation Device

- The seismic isolation device shall be able to maintain its functions in the presence of a seismic load caused by the design basis ground motion that is appropriately defined corresponding to the classification of seismic importance.
- The allowable displacement limit of the seismic isolation device shall be determined by an appropriate method and the utility shall demonstrate the validity of the allowable displacement limit.
- The allowable displacement limit may be determined using either of the following methods:
  (i) Determination from the ultimate displacement of the seismic isolation device or the crossover piping that connects between base-isolated building/equipment and non-isolated building/equipment.
  (ii) Determination from the viewpoint of satisfying performance goals for core damage frequency and containment failure frequency based on the risk assessment.
  Specifically, the methodology of seismic PSA is can be used in the second method (ii).

(Commentary)

- *Allowable limits for steel frame*

Reference shall be made to the allowable stress levels used in the design of conventional non-isolated structures at nuclear power facilities.

- *Allowable limit for seismic isolation elements*

See Section 3.3 "Basic Performance Requirements for Seismic Isolation Device" for discussions on allowable limit for seismic isolation elements.

- *Dampers and other seismic isolation elements with a moving mechanism need to have their allowable limit confirmed by testing. The dynamic properties of the base-isolated structure (response acceleration, velocity, displacement, etc.) shall be monitored while testing and the testing should cover full ranges of anticipated dynamic properties.*
  Such testing may be omitted, however, if allowable limit can be determined by an alternative method.
- *The implementation of the base-isolated structure may significantly affect the seismic safety of crossover piping, etc., because of increased displacement during earthquake. Therefore, when designing the seismic isolation device, it is necessary to determine the allowable displacement limit by an appropriate method and to demonstrate the validity of the allowable displacement limit.*
- *The allowable displacement limit of the seismic isolation device may be determined using either of the following methods:*
  (i) Determination from the ultimate displacement of the seismic isolation device or the crossover piping that connects between base-isolated building/equipment and non-isolated building/equipment.
  (ii) Determination from the viewpoint of satisfying performance goals for core damage frequency and containment failure frequency based on the risk assessment.

3.6.3 Allowable Limit for the Superstructure and the Substructure

- Superstructure

With building isolation, the allowable limits for the building shall be defined to satisfy the criteria on the allowable stress prescribed by commonly accepted safety standards and guidelines, as a general rule. The allowable limits for facilities that are placed on a building structure shall be as prescribed by the New Rules. With equipment isolation, the allowable limits shall be as prescribed by the New Rules.

- Substructure

The allowable limits for the substructure shall be as prescribed by the New Rules.

(Commentary)

- *Building isolation*

Since seismic isolation structures have a relatively long natural period, the superstructure is subjected to semi-static load. If the superstructure gets into plastic state during earthquake, it is possible that the plastic deformation of the superstructure would significantly increase. Considering that, it shall be ensured that the allowable limit for the building satisfy the criteria on the allowable stresses established by commonly accepted safety standards and guidelines, as a general rule. In the case of building isolation, the allowable limit for facilities that are placed in the building shall be as prescribed by the New Rules.

- *Equipment isolation*

The allowable limits for facilities shall be as prescribed by the New Rules.

- *The allowable limit for the substructure shall be as prescribed by the New Rules, according to conventional design practices.*

4. REVIEW ON RISK ASSESSMENT STAGE

4.1 Approaches to Risk Assessment for Base-Isolated Structure

- When implementing the base-isolated structure, the presence of "residual risks" shall be acknowledged and efforts shall be made to make it as small as practicable.

4.2 Methodology of Risk Assessment for Base-Isolated Structure

- The residual risks can be evaluated by probabilistic safety assessment methods, specifically, the methodology of seismic PSA.
- A methodology other than that of seismic PSA may be used, provided that its validity is demonstrated.

5. REVIEW ON CONSTRUCTION STAGE

5.1 Quality Control for Seismic Isolation Elements

- For assurance of the quality of seismic isolation elements throughout the in-service period, the procurement, production, inspection, installation of seismic isolation elements, checking clearance gap from adjacent structure, performance testing of seismic isolation elements including displacement gauging device, etc., shall be done with an appropriate quality assurance program equivalent to the one applicable to the superstructure.

(Commentary)

- *Quality control activities at nuclear power plants are conducted with appropriate quality control programs for all stages from the design stage to the operation stage.*
- *Since any failure of seismic isolation elements may directly lead to the failure of superstructure, the level of quality control for seismic isolation elements shall be equal to that for the superstructure and substructure.*
- *For quality control of seismic isolation elements, it is important to be able to understand the characteristics of seismic isolation elements under actual service conditions during the in-service period. Therefore, the quality control of seismic isolation elements shall mainly rely on characteristic testing and product inspection and the inspection shall cover all products, as a general rule.*
- *In the case where the product inspections are limited, it shall be combined with characteristic test result, etc., to make the quality control more comprehensive.*
- *In Section 3.4.6 "Seismic Isolation Element Characteristics for Seismic Response Analysis", it has been stated: "Upon the completion of seismic isolation elements for actual implementation, the characteristics such as stiffness and damping factor shall be evaluated by testing all products, as a general rule, in order to confirm the validity of the seismic isolation element characteristics used in seismic response analysis." As prescribed, the characteristics of seismic isolation elements confirmed by the inspection mentioned above should be used for verifying the characteristics used for the seismic response analysis.*
- *It is necessary to check the clearance gap between seismic isolation device and adjacent structure, installation and availability of displacement gauging device and implementation of performance testing of seismic isolation device.*

5.2 Pre-service Inspection of Base-Isolated Structure

- Before starting operation of the power plant, the utility shall inspect the base-isolated structure to confirm the availability of required functions.
- The inspection data must be recorded.

(Commentary)

- *During the pre-service inspection, the utility shall visually inspect the seismic isolation devices, take measurements and keep records to confirm the seismic isolation device has been properly constructed.*

  In addition, the utility shall inspect the base-isolated structure for its capability of motion during earthquake (e.g. ensuring the absence of obstacle such as inappropriate implementation of crossover components which disturb the motion of the base-isolated structure) by both visual inspection and testing (static load testing, for example). However, it is not meant to require the testing if conducting test is evidently difficult.
- *The utility shall plan periodical inspection programs clarifying the items to be addressed in the inspections and record initial inspection data. Those data would be compared with data measured in the in-service inspections.*
- *See "Maintenance Standard for Seismically Isolated Buildings" (2007) from the Japan Society of Seismic Isolation (JSSI) for information about the method of pre-service inspection of seismic isolated buildings and about the values to be inspected. No maintenance standards have been prepared for the equipment isolation; the above standards for the building isolation may be referred to in the meantime as the source of some useful information.*

5.3 Performance Confirmation of Seismic Isolation Structure

- Vibration characteristics of the seismic isolation structure such as natural frequency, damping ratio shall be evaluated by performance confirmation testing, etc.
- Testing results related to property of seismic isolation shall be recorded.

6. REVIEW ON OPERATION STAGE

6.1 In-service Inspections

- The seismic isolation device shall maintain the required functions throughout the in-service period. To ensure that, it is necessary to inspect the base-isolated structure periodically.
- In a situation where product tests with specimen which is separately kept under the environment condition same with actual device or static load test, those tests should be conducted.

(Commentary)

- *The utility shall plan in-service inspection programs in order to inspect base-isolated structure periodically. The utility may refer to "Maintenance Standard for Seismically Isolated Buildings" (2007) from JSSI for information about maintenance methods and control values for the building isolation. No maintenance standards have been prepared for the equipment isolation; the above standards may be referred to in the meantime as the source of some useful information.*
- *Visual inspection and measurement shall be the methods used in the in-service inspections.*

- *In a situation where product tests with specimen which is separately kept under the environment condition same with actual device or static load test, those tests should be conducted.*
- *If inspection reveals a change in the performance of seismic isolation elements due to causes such as aging, the utility shall verify, by means of seismic response analysis, for example, that the seismic isolation device still maintains the required functions.*
- *When the specifications of the superstructure greatly change from the situation in the design stage (e.g. change of mass due to the replacement of equipment in the case of equipment isolation), the utility shall evaluate the impact of the change.*

6.2 Performance Verification during/after Earthquake

When earthquake occurs, the response of the base-isolated structure shall be monitored by an appropriate method. Depending on the magnitude of seismic response, the integrity of the superstructure, substructure and seismic isolation device shall be checked for the detection of any damage, the current position of the base-isolated structure shall be determined, and the performance shall be verified that the base-isolated structure maintains required functions.

(Commentary)

- *To enable the monitoring of the seismic response of the base-isolated structure during earthquake, the utility must install accelerometers and displacement gages to appropriate positions.*
- *The behavior of the base-isolated structure during earthquake is confirmed by the magnitude of relative displacement between the superstructure and substructure, by the response acceleration measured immediately above the seismic isolation story, or in terms of the both. The utility shall monitor the orbits and seismic response acceleration of the base-isolated structure during earthquake.*

  Even though compromise may be allowed if the installation of above-mentioned instruments is difficult due to restrictions imposed by the size of the base-isolated structure, the utility shall make the best effort to enable the measurement of orbit.
- *The performance verification of the base-isolated structure shall involve the confirmation of structural integrity and required functions.*

7. DOCUMENTATION MANAGEMENT OF DESIGN DATA, MONITORING DATA, ETC.

- *With each implementation of the seismic isolation structure, the utility shall keep records of design data, etc.*
- *The utility shall keep monitoring data of the base-isolated structure recorded during earthquake.*

DEFINITION OF TECHNICAL TERMS

Terms	Definition
Seismic isolation system	Complete set of equipment and structures necessary to perform the isolation function. It includes all the isolators, their supports, and their anchorages, if any.
Isolator or Seismic isolation device	Elementary component of the seismic isolation system located between the substructure and the superstructure and performing the needed seismic isolation function. (e.g. association in parallel of a rubber bearing or springs and a damping device).
Seismic isolation element	Smallest unit in an isolation device (e.g. laminated rubber, springs, or dampers).
Seismic isolation story	Space between a superstructure and a substructure, where the isolators are installed.
Base isolated superstructure	Structure effectively isolated by the seismic isolation system. The superstructure is built on the isolators but does not include them. For isolated buildings, it generally comprises the upper raft (or basemat) and the building structures.
Substructure or infrastructure	Structure supporting the seismic isolation system. The substructure is below the base isolation story and the isolators but does not include them. For isolated buildings, it generally comprises the lower raft (or basemat), pedestals or walls supporting the isolators and the moat walls.
Base-isolated structure	Structure consisting of a superstructure, a substructure, and an isolation system.
Non-base-isolated structure	Structure where seismic isolation is not applied (buildings, facilities).
Umbilical or system connection or crossover structure	Equipment or system running from a base isolated structure to its non-base isolated (or separately base isolated) environment. Examples are electrical cables located in trays, high-pressure steam lines connecting the nuclear island to the turbine, low pressure safety water lines, etc.
Equipment isolation	Collective term for equipment, system or floor seismic isolation system.
Floor isolation	Floor seismic isolation system.

Terms	Definition
Fail safe system	System preventing the excessive drift of the superstructure potentially leading to a failure of the seismic isolation. system. A hard stop is a typical example of fail-safe system for base isolated structure.
Pedestal	Part of the substructure supporting one or several isolator(s). It is usually a (short) column or wall fixed to the lower raft. It is designed to carry the loads transmitted by the isolators and to allow inspection and replacement of these isolators.
Moat	Space surrounding the superstructure to allow for its movement without constraints during a seismic event. The definition of the moat width is an important design condition.
Moat protection structure	Structure protecting the moat from intrusion of water, airplane kerosene and possibly others.
Lateral (retaining) wall	External wall of the moat volume retaining the soil pressure around the seismic isolation system.
Hard stop	Structure or series of structures designed to prevent excessive displacement of the superstructure relative to the substructure by mean of mechanical contact.
Isolation system drift	Relative displacement between the superstructure and the substructure.
Vertical isolation system	System providing isolation of SSC in vertical direction only.
3D Isolation system	System providing isolation of SSCs in all 3 directions of the seismic excitation.

ABBREVIATIONS

BDB	Beyond Design Basis
BWR	Boiling Water Reactor
CQC	Complex Quadratic Combination
DBE	Design Basis Event
DSHA	Deterministic Seismic Hazard Assessment
GRS	Ground Response Spectrum
HDR	High Damping Rubber Bearing
LDRB	Low Damping Rubber Bearing
LRB	Lead Rubber Bearing
NPPs	Nuclear Power Plants
PGA	Peak Ground Acceleration
PSA	Probabilistic Safety Assessment
PSHA	Probabilistic Seismic Hazard Assessment
PWR	Pressurized Water Reactor
SEL	Seismic Equipment List
SI	Seismic Isolation
SIS	Seismic Isolation System
SPSA	Seismic Probabilistic Safety Assessment
SSCs	Structures, Systems and Components

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Vienna, Austria, 25-27 June 2012
Vienna, Austria, 4-6 November 2013
Vienna, Austria, 27-28 March 2014

IAEA
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No. 26

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20-01414E

International Atomic Energy Agency
Vienna
ISBN 978–92–0–106520–9
ISSN 1011–4289