SCK•CEN
STUDIECENTRUM VOOR KERNENERGIE
NUCLEAIRE

**BOOK OF ABSTRACTS**
SCK•CEN-BA-54

# SILER International Workshop 2013

## Rome (Italy), June 18-19, 2013

Centro Congressi
Piazza della Pilotta, 4
00187 ROMA - ITALIA

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# AGENDA

## Day 1 (June 18th, 2013)

| | |
|---|---|
| 08:30 – 09:00 | Registration – Welcome |
| | Topic 1: Modelling of systems & isolators for dynamic analyses |
| | **Session Chair: P. Sollogoub** |
| 09:00 – 09:40 | US Status on Lead-cooled Fast Reactors and Comments on Seismic Research, C. Smith (SILER EAC) (keynote lecture) |
| 09:40 – 10:20 | Siting of standard design power reactors in high seismicity areas by means of seismically isolated foundations, F. Allain (EDF), V. de Cesare (ENEL), A. Poggianti (ENEA) & P. Contri (ENEL) (keynote lecture) |
| 10:20 – 10:50 | French experience and practice of seismically isolated nuclear facilities - part I - Main considerations, M. Connesson & S. Diaz (NUVIA), F. Allain (EDF), N. Moussalam (AREVA) & I. Petre Lazar (EDF) |
| 10:50 – 11:10 | Break |
| | **Session Chair: S. De Grandis** |
| 11:10 – 11:40 | Ductility demand for base isolated structures and equipment. Implication for design & beyond design conditions, P. Sollogoub & I. Politopoulos (SILER EAC) |
| 11:40 – 12:10 | Dynamic behaviour of APR1400 nuclear Power plant with base isolation system, S.R. Han, S.H. Lee, C.G. Seo & H.S. Park (KEPCO) |
| 12:10 – 12:40 | Modelling strategies for the generation of floor response spectra of a base isolated nuclear structure, N. Moussallam (AREVA) |
| 12:40 – 14:00 | Break for lunch |
| | **Session Chair: A. Whittaker** |
| 14:00 – 14:30 | *The seismic fragility of the base-isolated NPP reactor building in the IRIS project, F. Perotti, M. Domaneschi (Politecnico di Milano) & S. De Grandis (SINTEC)* |
| 14:30 – 15:00 | *Seismic isolation of an ADS Reactor Building, A. Carrasco López & J. Gallego de Oteiza (EA)* |
| 15:00 – 15:30 | Seismic isolation of LFR Reactor Buildings, G. Moretti & U. Pasquali (SRS) |
| 15:30 – 16:00 | Advanced numerical models for elastomeric & sliding isolators, M. Kumar, M. Kumar, A. Whittaker & M. Constantinou (University of Buffalo) |
| 16:00 – 16:20 | Conclusions of topic 1 |
| 16:20 – 16:40 | Break |
| | Topic 2: Development, fabrication & testing of isolation systems |
| | **Session Chair: M. Forni** |
| 16:40 – 17:20 | HDNR-Seismic Isolators, performance and historical development, H. Ahmadi (TARRC) (keynote lecture) |
| 17:20 – 17:50 | Elastomeric isolators for nuclear power plants, M.G. Castellano (FIP) |
| 17:50 – 18:20 | French experience and practice of seismically isolated nuclear facilities - part II - implementation (from fabrication to construction), M. Connesson & S. Diaz (NUVIA) |
| 18:20 – 18:40 | Conclusions of topic 2 |
| 18:40 | End of Day 1 |

# AGENDA

## Day 2 (June 19th, 2013)

| | |
|---|---|
| 08:30 – 09:00 | Start of meeting |
| | Topic 3: Sloshing in seismic isolated reactors |
| | **Session Chair: W. Villanueva** |
| 09:00 – 09:30 | Preliminary evaluation of the Fluid-Structure Interaction effects in a LFR, R. Lo Frano & G. Forasassi (University of PISA) |
| 09:30 – 10:00 | Parametric study of sloshing in the primary system of an isolated LFR, M. Jeltsov, W. Villanueva & P. Kudinov (KTH) |
| 10:00 – 10:30 | Sloshing effects in LFR systems, G. Barrera (CIEMAT), P. Dinoi, J. Cercós & L. González (UPM), F. Beltrán & A. Moreno (IDOM) |
| 10:30 – 10:50 | Conclusions of topic 3 |
| 10:50 – 11:10 | Break |
| | Topic 4: Design guideline & economics for seismic isolated systems |
| | **Session Chair: D. De Bruyn** |
| 11:10 – 11:50 | The Non-inclusion of HDNR by USNRC, J. Kelly (UC Berkeley) (keynote lecture) |
| 11:50 – 12:20 | The new performance oriented European standard EN15129-Anti seismic devices, R. Medeot (CEN-TC) |
| 12:20 – 12:50 | Guidance for the seismic isolation design of nuclear structures, A. Whittaker (University of Buffalo), A. Kammerer (US NRC), M. Constantinou (University of Buffalo) & M. Salmon (Los Alamos) |
| 12:50 – 13:10 | Conclusions of topic 4 |
| 13:10 – 14:30 | Break for lunch |
| | Topic 5: Interconnection systems for seismic isolated systems |
| | **Session Chair: B. Yoo** |
| 14:30 – 15:00 | Seismic isolation of reactor assembly for a fixed base ADS reactor building, B. Yoo & D. De Bruyn (SCK•CEN) |
| 15:00 – 15:30 | Development of Pipe Expansion Joint for isolated LFR/ADS, H. Nowak (BOA) |
| 15:30 – 16:00 | Development of Fail Safe system for isolated LFR & ADS, A. Poggianti (ENEA) |
| 16:00 – 16:20 | Conclusions of topic 5 |
| 16:20 – 16:40 | Break |
| 16:40 – 18:00 | General discussion<br>Moderators : session chairs and invited lecturers (C. Smith, F. Allain, H. Ahmadi, J. Kelly, P. Sollogoub, A. Whittaker,W. Villanueva, M. Forni, S. De Grandis, B. Yoo, D. De Bruyn) |
| 18:00 | End of Day 2 |

# French experience and practice of seismically isolated nuclear facilities – Part I: Main considerations

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Seismic isolation (SI) has been widely used to protect civil structure, mainly bridges but also buildings. The lesson learnt after decades of design and practice in bridge applications – where the environmental conditions are dramatically more severe in comparison to nuclear facilities – has demonstrated that it is a very robust technology.
However, SI is not yet commonly used for the protection of nuclear facilities. This comes in part as a result of the lack of specific standards and of the resources needed to test full-scale isolators. Therefore, an adaptation of the civil standards is required before applying them to the nuclear field.

This presentation is aimed at summarizing the current practice for the implementation of seismic isolation in France and the reasons for the technological choices which were made in relation with isolation-focused Safety-related topics.
A more detailed synthesis is to be issued by the authors of this presentation to support IAEA in its effort to issue guidelines on seismic isolation systems for nuclear facilities. This synthesis will be available in AFCEN (2013).

Main considerations
An overview of the different French applications and the main characteristics of their isolation system is given.

The design process is detailed. First of all, the isolator design is oriented by some Safety-related requirements which have to be taken into account from the early design stage:

- fire resistance of the isolation system
- robustness and durability of the isolation system, in order to avoid any cliff-edge effect
- proper transmission of the loads between the isolated structure and the foundations

The way French owners and isolation manufacturers chose to fulfill each one of these requirements is then detailed to give a comprehensive synthesis on the subject.

Then, a key issue is to feed the design process with measured values. Input data needed at this stage are: - isolators mechanical properties, coming with production ranges. For meter-size isolators, the classical available formulae used to calculate these properties from the geometrical characteristics of the isolators may not be as accurate as designer would expect.

- aged mechanical characteristics, at the end of service life.

Therefore, a preliminary tests campaign is required in order to qualify accurate initial and aged values.

Implementation – from fabrication to construction
At last, not only the fabrication of the isolators but also the installation phase on site will practically address the same Safety-related topics. Typically, producing numerous isolators with accurate mechanical characteristics leads to an in-depth production quality follow-up, whose backbone architecture based upon EN 15129 standards, will be presented.

Other implementation feedback gained over French applications will also be assessed.

# Modeling strategies for the generation of floor response spectra of a base isolated nuclear structure

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In the nuclear industry in general, and for gen IV reactors in particular, the main objective of implementing a base isolation system below a structure is to decrease the loads on the systems and components. These loads are typically represented by in-structure acceleration time histories or floor response spectra at the systems and components anchoring points within the structure. The determination of these loads requires the use of adequate models for both the isolation system and the structure. An extensive documentation exists on the modeling of base isolation systems, including systems with significantly non linear behaviors. Many works are also ongoing on this subject. The present paper addresses the modeling strategies for the structure. It focuses on two practical aspects that have historically been disregarded when generating floor response spectra or in-structure acceleration time histories within a base isolated structure.

The first practical aspect is the importance of the coupling between the seismic excitation in the vertical direction and the in-structure local response in the horizontal direction. This aspect has been identified in the recent projects of isolated nuclear structures in France. It has been properly documented by several authors since then and the present paper only summarizes these works (see [1] and [2]).

The second practical aspect is the modeling of damping within the superstructure. Damping is typically introduced in a building model either in the form of modal damping values or in the form of a proportional (also called Rayleigh) damping matrix. In the case of a linear isolation system, such as the low damping rubber bearings used by the French nuclear industry for years (see [3]), both types of damping representations are acceptable. In the case of a non linear dissipative isolation system, such as high damping rubber bearings, lead plug rubber bearings or any system relying on friction to dissipate energy, none of the two traditional damping representations are adequate. The workaround is either to use sub-structuring techniques, coupled to the use of a modal damping or to develop a proportional damping matrix in a relative coordinate system. The problems arising from the use of traditional damping models and the associated workarounds are detailed in the present paper.

**References**

[1] Moussallam, N., Vlaski, V. (2011). "Respective role of the vertical and horizontal components of an earthquake excitation for the determination of floor response spectra of a base isolated nuclear structure – Application to Gen IV reactors." *Transactions, SMiRT-21, 6-11 November, 2011, New Delhi, India. Paper ID# 80.*

[2] Politopoulos, I., Moussallam, N. (2011). "Horizontal floor response spectra of base-isolated buildings due to vertical excitation." *Earthquake Engng Struct. Dyn. 2011, Vol 41, pp. 587-592.*

[3] Moussallam, N., Allain, F., Petre-Lazar, I., Connesson, M., Diaz, S., Vu, T., Bouteleux, S., Soupel, B., Labbé, P., Thiry, J.M (2013). "Seismic Isolation of Nuclear Structures – Overview of the French Practice and Experience." *Transactions, SMiRT-22, 18-23 August, 2013, San Francisco, California, USA.*

# Ductility demand for base isolated structures and equipment. Implication for design & beyond design conditions

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Seismic base isolation is a very efficient way to improve the seismic resistance of structures, components and, specifically, nuclear facilities; one of the benefits is the decrease of acceleration on equipment in the facility. Nevertheless, components on seismically isolated exhibit a specific mechanical behavior in case of non linear excursions during the seismic event. In fact, the ductility demand innon linearly responding components is significantly higher than the demand for the same component located in a conventional, non isolated, structure. Although, the phenomenon is well known and easily understandable, the consequences for design and beyond design of isolated facilities and for their fragility evaluation are not considered in general.
The aim of the paper is to illustrate the basic mechanism and to present simulation results in order to quantify the effect. Some recommendations for design and beyond design approaches will be suggested.

# US Status on Lead-cooled Fast Reactors and Comments on Seismic Research

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The past history and current status of Lead-cooled Fast Reactor research in the US are reviewed and summarized. Key issues requiring research are identified, including seismis design. Addressing the response to seismic input is an important concern, as it is with other nuclear reactor concepts, especiaaly where there is the potential for siting in regings known to be seismically active. Comments are provided on current issues of seismic research in the US.

# Siting of standard design power reactors in high seismicity areas by means of seismically isolated foundations

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ENEL and EDF are jointly developing a feasibility study for the seismic isolation of EPR™ Nuclear Power Plant.

The application field of this project aims at broadening the adaptability of EPR™ standard design to all sites with high seismicity, typical of most sites of Italian territory, characterized by more severe values of seismic actions than those defined in the EPR™ standard project. The particularity of this pioneering study consists also in the unfamiliar use of seismic isolation solutions with very soft soil characteristics.

The seismic protection of the nuclear buildings by means of seismic isolators has been chosen in order to minimize changes to the standard design of the civil works and internal components of the EPR™ Nuclear Power Plant. The work will lead indeed to the identification of the optimal design solution, in terms of type and location of seismic devices, to achieve compliance to the floor response acceleration spectra in horizontal and vertical direction as defined in the EPR™ standard project, with levels of horizontal displacements not exceeding the maximum acceptable values for structural and non-structural elements.

The ENEA agency was commissioned by ENEL to perform the sizing of the seismic isolation system and the definition of the preliminary layout of isolators. These results are used as starting point for transient dynamic analyses, including soil-structure-interaction, aimed at assessing the behaviour of the whole isolated structure.

Moreover, the study explores the main issues that rise in case of application of seismic isolation systems to nuclear installations such as durability and inspection requirements, maintenance, replacement and qualification process.

# The seismic fragility of the base-isolated NPP reactor building in the IRIS project

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In past research a numerical procedure for computing the seismic fragility of equipment components in traditional nuclear power plant buildings was proposed. The procedure was based on the hypothesis of linear behaviour of the building; it was also assumed that no significant interaction exists between the dynamic behaviours of the building and of the equipment.

In terms of structural analysis, the key steps of the procedure were the development of a FE model for the building and the performance of step-by-step dynamic analysis for estimating the response statistics under random seismic input. In such setting the direct use of Monte Carlo Simulation to compute failure probabilities is a prohibitive task. For this reason the Response Surface Method was used for modelling the influence of the selected random variables on the building response; the fact that for a linear system the building performance can be described in terms of dynamic amplification was also exploited. More precisely the ratio a/ag of the peak acceleration at the component supports to the peak ground acceleration was considered to define the building performance.

A Central Composite Design was adopted to define the experiments necessary to estimate the Response Surfaces; the latter delivered the parameters governing the extreme values of seismic response. From these, the probability of exceeding a given amplification factor Pexc(a/pga) was obtained, via Monte Carlo Simulation, for all amplification values in the selected range.

A procedure for refining the RSs was also proposed, based on the computation of the seismic risk in terms of annual probability of failure for a prototype site and for a given value af of the support acceleration leading to collapse. By denoting with pPGA(pga) the PDF of the annual extreme of the PGA, the risk is equal to the convolution of the conditional probability Pexc(af /pga) and the pdf pPGA(pga). By investigating the integrand function in the convolution, the PGA range delivering the largest contributing to the total risk is defined: from this the amplification range in which the RS's must be refined is stated.

When seismic isolation is introduced, resulting in a dramatic reduction of horizontal accelerations inside the building, attention is focused, in the fragility analysis, on the behaviour of the adopted isolation devices (High Damping Rubber Bearings); since a complete experimental characterization of the HDRB behaviour at failure is still lacking, the fragility analysis of the isolators has been initially based on the value of the relative displacement across the isolator. As a second option the definition of a first-damage condition, associated to the reaching of a limit value of the bond stress between the rubber and the steel plates, will be pursued. The definition of the limit-state surface, formulated in terms of horizontal and vertical loads acting on the device, will be based on a simplified analytical formulation, supported by both numerical and experimental tests.

Since the behavior of the HDRB isolators is markedly hysteretic, the hypothesis of linearity of the building response is removed in the dynamic analyses, and a suitable force-displacement literature model is adopted to represent the isolators inelastic response to horizontal loading. In such setting, the Response Surface evaluation must be repeated for every value of peak ground acceleration; on the other hand, to evaluate the isolators' behavior, the seismic behavior of the isolated building can be captured by means of a very simple mechanical model which can be based on the hypothesis of rigid-body motion of the building.

On this basis, the procedure for fragility analysis was applied focusing on the uncertainties related to the isolators behavior. An example of application regarding a preliminary design of the base isolation system of the reactor building within the IRIS international project will be shown.

# Seismic isolation of LFR Reactor Buildings

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The attention of this research is focused on the evaluation of the effects of earthquakes (with particular regards to beyond design seismic events) in a LFR reactor system applied to the ELSY project considering the effect of isolation devices.

Consequences of seismic hazard are relevant to a wide range of damage related not to the structural failure only, but to other phenomena that can be summarize into:

1. structural failures due to the dynamic loading (loss of coolant from primary system, steam generator fealure etc)
2. core voiding by gas entrapped into primary coolant system,
3. functional failures of equipment due to coolant spill-out.

Seismic consequence can be mitigate by the introduction of seismic isolation that is considered an effective method for reducing or almost eliminating the devastating effects of earthquakes. In particular, the use of this system can provide higher safety margins against failure of equipment and structural components, because the acceleration level at which the safe shutdown occurs can be significantly increased. Beside, the increasing of the absolute displacement shall be tuned by suitable design of stiff and damping of the isolation devices.

The aim of the seismic calculation performed in this study, is to evaluate the response, in term of displacement and acceleration of the reactor building for different soil type, earthquake excitation, and type of isolation devices (HRB and LRB).

Points considered for the analysis are located in correspondence of the main equipments, pipes and primary or secondary nuclear systems in order to give them a complete input for the design of their joints and components.

A numerical FE model of the ELSY reactor systems has been realized and non linear time history analysis has been carried out by the software ABAQUS.

The soil structure interaction has been modeled by lumped springs for each degree of freedom, at the bottom of the FE model foundation

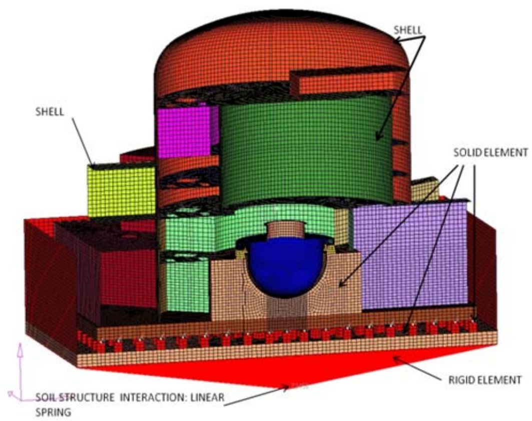
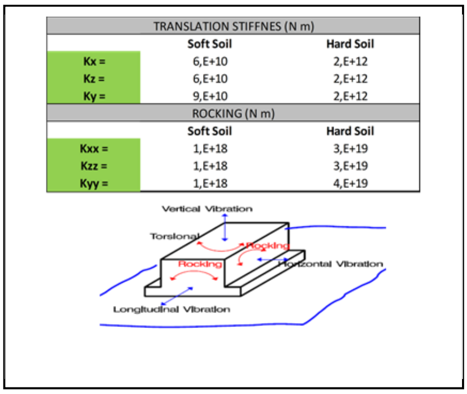



Figure 1: FEM model

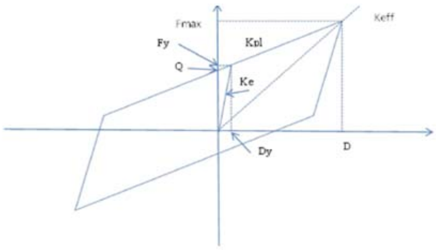


| TRANSLATION STIFFNES (N m) | | |
|---|---|---|
| | Soft Soil | Hard Soil |
| Kx = | 6,E+10 | 2,E+12 |
| Kz = | 6,E+10 | 2,E+12 |
| Ky = | 9,E+10 | 2,E+12 |
| ROCKING (N m) | | |
| | Soft Soil | Hard Soil |
| Kxx = | 1,E+18 | 3,E+19 |
| Kzz = | 1,E+18 | 3,E+19 |
| Kyy = | 1,E+18 | 4,E+19 |



Figure 2: Soil structure interaction

The isolation devices have been preliminary designed and tested for this specific project and they have been modeled by a bi linear behavior.




| | | |
|---|---|---|
| Max displacement D | mm | 250 |
| Period | s | 1.75 |
| Global mass | kg | 1.363E+08 |
| N isolators | | 225 |
| K total | Mn | 1.762E+09 |
| K eff | Nm | 7.830E+06 |
| Damping C cr | Kgm/s | 9.801E+08 |
| Cycle area | Joule | 3.075E+05 |
| Damping coefficient | | 0.100 |
| Damping single isolator | Kgm/s | 4.356E+05 |
| Q | N | 3.345E+05 |
| F max | N | 1.958E+06 |
| F y | N | 4.654E+05 |
| Elastic displacement Dy | m | 0.020 |
| K pl | Nm | 6.493E+06 |
| K el | Nm | 2.308E+07 |
| H rubber height | m | 0.256 |
| G shear modulus | MPa | 1.4 |
| Total rubber area | m² | 3.171E+02 |

| | | |
|---|---|---|
| Max displacement D | mm | 250 |
| Period | s | 2.5 |
| Global mass | kg | 1.363E+08 |
| N isolators | | 225 |
| K total | Mn | 8.609E+08 |
| K eff | Nm | 3.826E+06 |
| Damping C cr | Kgm/s | 6.851E+08 |
| Cycle area | Joule | 3.005E+05 |
| Damping coefficient | | 0.2 |
| Damping single isolator | Kgm/s | 6.090E+05 |
| Q | N | 3.267E+05 |
| F max | N | 9.566E+05 |
| F y | N | 3.771E+05 |
| Elastic displacement Dy | m | 0.02 |
| K pl | Nm | 2.520E+06 |
| K el | Nm | 1.885E+07 |
| H rubber height | m | 0.25 |
| G shear modulus | MPa | 1.4 |

**Figure 3: Isolation device modelling**

Artificial accelerogram used for simulating the seismic excitation, has been generated by the design response spectrum calculated in according to the Regulatory Guide 1.6 and the Eurocode 8.

A data base of the response time history far all interface points overall the reactor building has been collected and used as reference for the design of the main nuclear component and flexible joint connections.

The benefit of the isolator on the design value of such components has been evaluated comparing results obtained considering the reactor building both under fixed and isolated foundation.

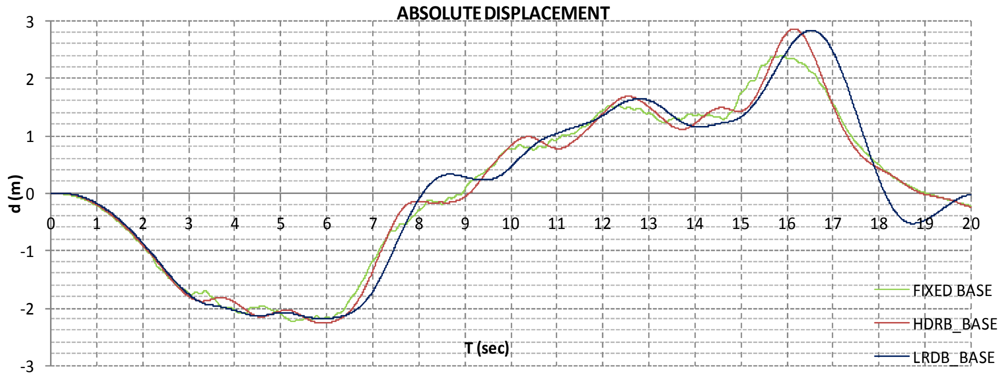



**Figure 4: Absolute horizontal displacement of the reactor vessel**

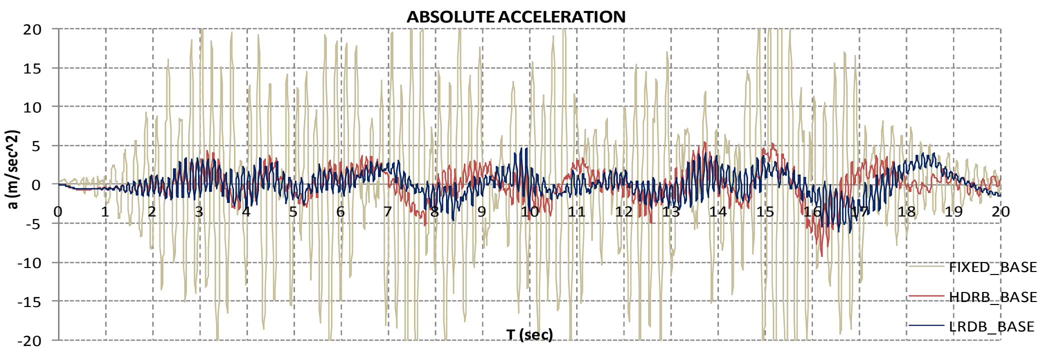



**Figure 5: Absolute horizontal acceleration of the reactor vessel**

# Seismic isolation of an ADS Reactor Building

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The SILER Project aims to study the risks associated with seismic events in Generation IV Heavy Liquid Reactors, and the protection measures that can be developed to reduce these risks. Special attention is given to the seismic behavior of such reactors when they are seismically isolated.

This paper presents the work developed to carry out one of the many subtasks that are part of this SILER project, the analysis of an Acceleration Driven System Heavy Liquid Reactor (based on the Myrrha project) with seismic isolation devices. Possible situations in terms of seismic input and isolation devices are proposed and considered, and a set of cases is analysed by means of Finite Element software and Time-Histories for displacements, velocities and acceleration. Lastly, floor response spectra are developed and presented along with the results of the study.

# Advanced numerical models for elastomeric & sliding isolators


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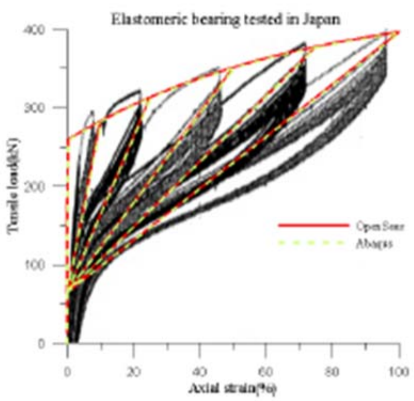
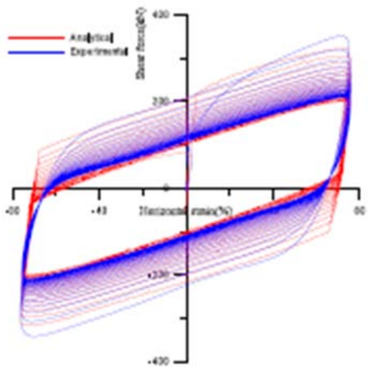
The forthcoming edition of ASCE 4 and seismic isolation NUREG will include requirements for isolation-system analysis using numerical models of isolators that can accurately capture response under design basis earthquake and beyond (extended) design basis earthquake shaking.

The US Nuclear Regulatory Commission is funding a research project at the Lawrence Berkely National Laboratory and MCEER at the University at Buffalo to develop, validate and document advanced models of elastomeric and sliding isolators and to implement the models in finite element codes such as OpenSees and ABAQUS.

The paper will present now models for elastomeric (natural rubber and lead-rubber) bearings and sliding bearings. The models for the elastomeric bearings capture cavitation under high tensile pressures (see lower left) compressive-tension-shear interaction, and change in hysteresis of lead-rubber bearings due to energy dissipation and heating the lead core (see lower right). The model for sliding (Friction Pendulum™) bearings captures the dependence of the coefficient of sliding friction on instantaneous pressure, temperature and sliding velocity, and accounts for the 2D motion of the articulated slider across the sliding surface.

The goal is to develop verified and validated models of isolators under extreme combinations of vertical and horizontal loadings. The models will be available in the open-source code OpenSees and the USNRC ESSI simulator for use by designers, applicants and regulators alike. The paper will describe the importance of modeling cavitation, axial-shear interaction and change in hysteresis for testbed safety-related nuclear structures deployed at existing power reactor sites in the United States.



# Dynamic behaviour of APR1400 nuclear Power plant with base isolation system

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This paper describes how APR1400 (Advanced Power Reactor 1400) NPP (nuclear power plant) with a base isolation system subjected to earthquakes behaves. The APR1400 is a Korean 1400MW class nuclear reactor designed to meet the future needs of the nuclear power industries and a few commercial plants with the APR1400 are being constructed. To identify dynamic response of the ARP 1400 NPP with a base isolation system, a prototype of the base-isolated ARP 1400 NPP is developed and SSI (Soil Structure Interaction) analyses are performed. The prototype of the base-isolated ARP 1400 NPP includes the same upper structure with the original ARP 1400 NPP and the thicker base concrete with optimized bearing arrangement. Two base-isolated systems are considered each using Lead Rubber Bearing (LRB) and Eradi-Quake System (EQS). In the analyses, two ground motions satisfying US NRC and EU criteria respectively are applied and baseline soil models permitted by US NRC and EU are considered. The horizontal and vertical responses of SSI analyses for two base-isolated systems are compared with the responses of non-isolated systems respectively. The results of SSI analyses show that the response of the APR1400 NPP with a base isolation system is significantly reduced horizontally.

**Keywords**: APR1400 NPP, Base isolation, SSI, LRB, EQS

# High Damping Natural Rubber Seismic Isolators
# Performance and historical development

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The first part of the paper will give a brief account of the historical development of High Damping Natural Rubber (HDNR) seismic isolators together with performance since their first application in 1985 in the Foothill Communities Law and Justice Centre, County of San Bernardino, California.

In the second part, the general dynamic and physical properties of HDNR will be presented and some of the important aspects of their design will be covered.

# Elastomeric isolators for nuclear power plants

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Nowadays, the design of nuclear power plants (NPP) is characterized by enhanced safety level. In particular, GEN III+ and GEN IV reactors have to be highly secure and designed to withstand extremely severe external events such as floods, tsunamis, tornadoes, plane crashes, fires and, in particular, earthquakes. Seismic isolation is considered the most promising technology to protect NPPs from a seismic attack, because it allows to strongly reduce the horizontal components of the acceleration, giving to the isolated structure a “rigid body” behaviour. Therefore, all the internal most critical components are subjected to the same horizontal acceleration, independently of their position in the building, allowing for a standardization of the plant, which can be designed independently of the construction site.

Within the framework of the SILER research project, elastomeric isolators have been designed for both LFR and ADS reactor systems. In particular, the reference reactors considered in the study are ELSY and MYRRHA. For each structure, both High Damping Rubber Bearings (HDRB) and Lead Rubber Bearings (LRB) have been designed. Due to the typical huge masses of the structures, and to the enhanced safety level required, the related isolators result to have very large sizes, both in plan and in height. This complicates the manufacturing process and the execution of the type tests. For application in NPPs, it is very important to know the behaviour of the isolators beyond the design conditions, thus tests up to failure are needed.

The first phase of the SILER project has been devoted to the development of special rubber compounds, both low damping and high damping, the first to be used in the LRB, and the latter in the HDRB. Quasi-static and dynamic tests on small scale isolators, up to 500 mm diameter, have been carried out for a complete characterization of the rubber compounds. The second phase has been devoted to the design of the isolators. For example, the HDRB isolator designed for ELSY have diameter of 1350 mm and total rubber height of 256 mm. The third phase is the manufacturing and testing of full scale prototypes of both HDRB and LRB. Particular attention has been focused in the planning of testing, aimed at reaching the failure of the isolators and thus gathering useful information for the seismic fragility analyses.

The paper presents the preliminary results; full results will be presented at the end of the activities.

**Keywords:** Elastomeric isolators, high damping rubber bearings, lead rubber bearings, nuclear power plants, testing.

# French experience and practice of seismically isolated nuclear facilities Part II - implementation (from fabrication to construction)

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General considerations

Seismic isolation (SI) has been widely used to protect civil structure mainly bridges but also buildings. The lesson learnt after decades of design and practice in bridge applications - where the environmental solicitations are dramatically severe in comparison to nuclear facilities – has demonstrated that it is a very robust technology.

However, SI is not so common in the state-of-the-art of the nuclear facilities especially due to the lack of specific standards and to the resources needed to test the full-scale isolators. Therefore, a nuclear insight on the civil standards is required. This paper details not only nuclear specificities based upon LWR lesson learnt at the SI design stage but addresses also the in-depth quality controls implemented at production stage. It focuses mainly with elastomeric-type isolators but the approach may be extended to any kind of base-isolation system.

Design

The design stage is rooted in the civil standards such as EN 15129. However, the Safety requirements, specific to Nuclear facilities, demand a more restrictive approach: design working ranges must be limited to safer limits; a full qualification program of the material and of the isolator must demonstrate the robustness of the design and the predictable, limited, effect of time (ageing over the time-life of the facility – 70 years typically) on the mechanical characteristics of the SI; replaceability of the isolators has to be considered as a design case from the very beginning.

Fabrication

A thorough quality follow-up is set up at the fabrication stage to guarantee the conformity and the health of the SI. Quality Related Activities are defined at the very beginning of the fabrication process. Factory Production Tests enables to monitor the actual production mechanical characteristics throughout the whole process.

Conclusion

The design Safety demonstration and the manufacturing extensive quality frame ensure that all the steps are under proper control. Therefore, this effort is logically extended after the commissioning of the factory through the SI monitoring program. Representative parameters are followed-up in order to confirm the assumptions qualified during the design and the fabrication stages.

# Preliminary evaluation of the Fluid-Structure Interaction effects in a LFR

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The aim of the study is to evaluate the structural effects (in terms of "global response") induced by a 'beyond design basis' earthquake (BDBE) on the main safety relevant structures and components of an isolated liquid metal reactor. To attain this purpose, as an example, a lead cooled system (e.g. ELSY or ALFRED projects) characterized by isolation devices, with appropriate hypotheses made to characterize the dynamic behaviour of the lead and reactor structures, was considered.

The isolation system was represented by using an iso-elastic approach.

Moreover the seismically induced hydrodynamic forces, the impact forces, exerted by the possible breaking waves, and the coupling effects between fluid and structures (fluid-structure interaction and "sloshing" phenomena), that may impair the integrity and/or the operating capabilities of the isolated LFR structures, were analyzed and determined.

In this framework it is important to note that, in the available in the open literature, the problems of the dynamic interaction of liquid sloshing with elastic or rigid structures are generally solved applying approximate linear theories or simplified approach in structures characterized by simple and regular shape.

To preliminary evaluate the BDBE effects, numerical calculations (i.e. non linear analysis) were hence carried out by means of appropriate dynamic FEM codes, implementing an external coupling, applying both the time history and the substructure approaches.

The adopted method allowed to represent the LFR reactor complex geometry behaviour and the effects induced by the arisen fluid motion that influences and is influenced simultaneously by the deformation of structure.

The preliminary results obtained were analysed with the intent also to check the considered nuclear facility safety margins and to contribute to a further step in the safety optimization of LFR systems.

A validation analysis was further performed to evaluate the consistency and adequacy of the obtained with the proposed method with respect to the ones achieved by the application of ASCE 4-98 rules mainly in terms of hydrodynamic pressure and forces.

# Parametric study of sloshing effects in the primary system of an isolated LFR

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Lead cooled fast reactor (LFR) has been selected by GIF (Generation IV International Forum) as one of the most attractive Gen-IV system. Commercial attractiveness of current LFR concept is achieved by application of pool-type design. The compactness of the design, however, also brings some safety issues pending for resolution. Risk related to sloshing of the heavy coolant due to seismic excitation is one of them. Sloshing may have adverse effects in the primary system due to (i) fluid-structure interaction (FSI) and/or (ii) gas entrapment in the coolant with possible subsequent transport to the core region. First effect can cause structural damage whereas second leads to reactivity insertion.

The European Lead cooled SYstem (ELSY) concept of a 600 MWe pool-type LFR is considered as a reference in this study. Computational Fluid Dynamics (CFD) analysis in conjunction with a risk oriented probabilistic approaches has been utilized. The main goal is to identify the domain of dangerous frequencies and magnitudes of the seismic response at the reactor vessel level that can lead to exceeding the safety limits for structural integrity and possible reactivity incretion.

In the first part of the study, different modes of sloshing are investigated using encompassing set of seismic input data regarding excitation frequencies and acceleration. An Eulerian Volume of Fluid (VOF) free surface tracking method is applied on a simplified domain of ELSY primary system comprising of lead coolant, argon gas and interface between them. Resulting shapes of the waves, hydrodynamic pressure distribution on structures and characteristics of the void formation/entrapment (e.g. amount, size distribution) are estimated.

The second part deals with the quantitative estimation of a probability that gas bubbles dispersed near the free surface are dragged by the coolant flow into the core region attributing to the risk of reactivity insertion or local damage of the fuel rods. Uncertainties in the drag correlation of bubbles in liquid lead and void characteristics are addressed. A probabilistic approach to estimate the void accumulation in the primary coolant is presented. Gas bubbles are modeled as Lagrangian particles with and without random-walk turbulent dispersion to account for the fluctuating nature of the velocity field.

Implications of the findings from the analysis to the reactor safety are discussed.

Presented work has been performed under the 7th Framework Programme project SILER.

**Keywords**: LFR, Sloshing, CFD, Lagrangian Multiphase, Reactivity Initiated Accident.

# Sloshing effects in LFR systems

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The effect of sloshing in the LFR reactor vessel supported on seismic isolators is being studied. The approach is to develop and compare the results with three different methodologies. In the first approach, a detailed model has been developed using FLUENT. The methodology is CFD (Computational Fluid Dynamics). The work includes the development of a detailed 3D model for interior surfaces of the reactor vessel in order to define, in as much detail as possible, the volume of the coolant and circulation ways of the fluid. The object is to obtain the evolution of the free surfaces of molten lead in the complex 3D model of the vessel with internals and, additionally, pressure time histories at different internal surfaces. These results will allow for the examination of the structural capability of different metallic elements associated with the vessel and its internal components

A second approach is being using which is based on ABAQUS and ALE methodology (Arbitrary Lagrangian Eulerian). The object of this work is to obtain the same results, as with FLUENT. However ABAQUS allows the study of the fluid structure interaction within the same computational model.

In a third approach the same simulation has been performed by a modern Lagrangian numerical method called SPH (Smoothed Particle Hydrodynamics). The weakly compressible version of the SPH methodology uses a discrete form of the mass and momentum conservation equations along with an equation of state linking the density and pressure fields.

A specific code has been developed in order to calculate the pressure and velocity fields of the fluid running on GPU (graphic process unit) cards, giving a highly efficient parallel computation. The number of particles used in these simulations is around 800k and the time required to complete 28 seconds of simulation is 20 hours using an ATI HD7950 graphics card with 1792 processors. Before this computation, a Cartesian grid, representing a simplified and covered version of the vessel, was created to set the initial boundary particles.

In all cases models have been processed with the accelerograms associated with a simplified model for vessel supported on a system of seismic isolators.

All these results are included in a comparative study to identify values, variables and critical methodologies

# The Non-inclusion of High Damping Natural Rubber by USNRC

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A draft report has been issued by the US Nuclear Regulatory Commission entitled "Technical Considerations for Seismic Isolation Nuclear Facilities" for consideration by interested parties. The report has been prepared by NRC and MCEER. It sets out to describe different types of isolators and makes recommendations. One of the sections of the report is shown below:

Properties of High Damping Rubber Bearings

High damping rubber (HDR) bearings use natural rubber with additives (or fillers) as the elastomer. These additives modify the mechanical characteristics of the rubber, including its hardness, stiffness, damping, elongation-at-break, creep and relaxation properties. The most important consequence of adding these fillers is the increase in damping of the elastomer. HDR bearings have damping ratios greater than 7% of critical, with some bearings having as much as 13% damping. [..] As noted earlier, due to scragging and unpredictable changes in properties over time, HDR bearings are not considered appropriate for use in NPPs, but are discussed here for completeness.

It is the purpose of this short note to take issue with the exclusion of High Damping Natural Rubber (HDNR) bearings for consideration as isolators for NPPs. The reason given for not including HDNR is that the scragging of bearings before installation leads to an uncertainty in the behavior of the bearing. This is based on observations of very high damping compounds developed by Bridgestone in Japan which use various oils and resins to achieve the high damping response. Other compounds with lower levels of damping have much less variation of response due to scragging. It is important to point out that the uncertainties in the behavior of HDNR bearings are much less than those in Lead Rubber Bearings (LRB) and Friction Pendulum (FP) bearings. Both of these types of bearings dissipate large quantities of energy in a small volume of the bearing. In the LRB the dissipation is in the lead plug itself. The dissipated energy manifests itself in heat which accumulates in the plug thus softening the lead. The lead is not a good conductor of heat and in any case the lead is in contact with the steel plates only across the very thin edges of the shims which are generally about 3 mm. in thickness. Conduction into the potential heat sink of the plates is negligible and radiation is impossible. The change in the yield stress of the lead due to this heat is largely unpredictable. In the FP bearings the energy dissipation is on the sliding and can generate very high surface temperatures. The stainless steel and Teflon are not good conductors of heat and a large part of the surface is covered by the articulated slider which prevents radiation. The consequence of these high surface temperatures on the friction, wear and surface stability is very uncertain.

In contrast, in the HDNR bearings the energy dissipation is produced through the whole volume of the compound meaning that there is less temperature rise for the same amount of energy dissipation and in addition the rubber is in contact with the potential heat sink of the steel plates over the entire surface of the steel. The result is that the behavior of the moderately damped HDNR is much less uncertain than for the other types of isolation systems.

There are further objections to use of LRB or FP bearings for nuclear power plants. The use of seismic isolation for these structures is not primarily to protect the structural system which by its nature is certain to be very robust but to protect equipment, piping systems and other sensitive non-structural elements. Isolation protects these by combining a stiff superstructure with a flexible foundation system. Such a combination provides a system that under seismic loading responds with almost rigid body motion in the superstructure and all deformation in the isolation system. The internal accelerations are very much lower than those of the corresponding fixed base response and relative internal displacements are eliminated leading to small inter-story drifts and all piping systems having the same input motion at all attachment points. However these benefits are only achieved if the isolation is close to linear with moderate damping. Some damping is always present in an isolation system using natural rubber but large values of even linear damping in a linear system can degrade the isolation effect and lead to the transmission of energy through the isolation interface.

The problem with LRB and FP systems in this context is that in both the damping level is very dependent on displacement, having large values at small displacements and decreasing steadily with increasing displacement. For example it is possible to have damping values in the range of 40-50% equivalent viscous damping at displacements of the order of a few centimeters dropping to 10% at displacements around 40-50 cm. Due to the extremely conservative seismic requirements for NPPs, the isolation systems for NPPs, will need to designed for large displacements and the design engineers will be tempted to try to reduce these displacements by adding damping. But adding damping at the design displacement will lead to very high damping (and high stiffness) at smaller displacements. This will mean that if the power plant experiences an earthquake event that is not as large as that implied by the design basis event, one that is more likely to be experienced by the plant over its working life, it will not be fully isolated. This will not be a problem for the structure but it will be a problem for the equipment, piping and non-structural elements.

The high damping and the high stiffness at these lower levels of input destroy the isolation process through several causes. The separation between the fixed base period and the isolation period is reduced increasing the floor accelerations in the superstructure and the high damping generates higher mode response. The lowest, primarily isolation, modes carry very little structural deformation but the higher modes generate structural deformation and internal accelerations. Higher mode response in FP is also produced by the fact that the response jumps from one branch of the hysteresis loop to another each time the relative velocity across the unit changes sign.

In effect it can be said that the LRB and FP put the damping in at the front end where it is not needed and do not at the design level where it is important. What is needed is a system that has low damping and low stiffness over the complete range of possible seismic input up to the design basis input but generates increasing stiffness and damping for beyond design basis input. This can be done with HDNR bearings that use what is referred to as crystallizing natural rubber.

This allows the design of a system that will permit full isolation for sensitive internal equipment at moderate levels of seismic input. The control of displacements at high levels of input is to be achieved by exploiting a property of natural rubber known as strain-induced crystallization. This phenomenon is well known and has been extensively studied for the behavior of thin sheets of rubber in tension. It is the reason for the inherent toughness of rubber in tension. It has been less well studied for rubber in shear but most natural rubber compounds will crystallize at some level of shear strain depending on the compounding and the amount of filler; it can range from 100% or higher but all natural rubber compounds will show the beginning of crystallization for shear strains around 200%. While it is possible to develop natural rubber compounds that have essentially no damping in the linear range it is actually easier to use compounds that have moderate levels of damping, e.g. equivalent linear viscous damping around 5% to 8% but another aspect of this crystallization process is that in addition to stiffening it leads to a very large increase in energy dissipation in the rubber.

The exploitation of the phenomenon of strain induced crystallization in natural rubber will permit the rational design of base-isolated nuclear structures for design basis and beyond design basis earthquake input and rather than blanket exclusion deserves further study and consideration.

# The new performance oriented European standard EN15129-Anti seismic devices

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On August 1st, 2011, the new European Norm EN 15129: Anti-seismic devices came into force in the European Union and other States members of the European Committee for Standardization (CEN).

The Norm was drafted by the Technical Committee CEN-TC 340 created by the CEN in 1993 with the mission to proceed with the standardization of anti-seismic devices for use in structures erected in seismic areas and designed in accordance with EUROCODE 8: Design of Structures for Earthquake Resistance, with the aim of modifying their response to the seismic action.

This European Standard specifies functional requirements and general design rules thereof, material characteristics, manufacturing and testing requirements, as well as acceptance, installation and maintenance criteria.

It deals with Permanent Connection Devices, Fuse Restraints, Temporary (Dynamic) Connection Devices, Displacement Dependent Devices, Velocity Dependent Devices (including hydraulic dampers), Isolators and combinations thereof.

General design rules, evaluation of conformity, installation and in-service inspection are the subject of other clauses that guarantee a uniform approach to the problem.

The final version of the European Standard on Anti-seismic Devices was completed in November 2007, when the comments received during the Public Enquiry were examined by the TC 340 for possible implementation.

The European Standard on Anti-seismic Devices (EN 15129) represents the most complete and up-to-date document in this field presently available to Seismic Design Engineers and Seismic Hardware Manufacturers.

In effect, said Standard aims to cover all types of Seismic Hardware in existence and leaves a door open to future progress.

This principally derives from the fact that the Standard is highly performance-oriented and this feature also constitutes per se a guarantee of equity between the various systems that may be used as alternatives.

The scope of the paper is that of illustrating the structure of EN 15129, the criteria adopted in its drafting, the procedures followed for its approval, and some of the aspects which render this document unique and innovative.

Finally, the paper compares the content of the European Standard on Anti-seismic devices with that of the American AASHTO Guide Specification for Seismic Isolation Design, underscoring the differences, as well as advantages and disadvantages.

# Guidance for the seismic isolation design of nuclear structures

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Seismic isolation is a viable method of protecting safety-related nuclear structures from the damaging effects of earthquake shaking. The soon-to-be completed USNRC NUREG on seismic isolation design and the forthcoming 2013 edition of ASCE Standard 4 will enable the horizontal seismic isolation of nuclear facilities such as nuclear power reactors and waste storage facilities.

Although the guidance in these documents focuses on building-type nuclear structures, they could be applied, in principle, to other structures, systems, and components, including small modular reactors and safety-related systems such as diesel generators.

Much of the guidance provided in Section 7.7 of ASCE 4 and the NUREG is common to both documents. The paper presents the performance objectives for Department of Energy facilities (covered by ASCE 4/43) and nuclear power reactors that are regulated by USNRC. Performance objectives are provided in terms of both conditional probabilities of failure for specified levels of ground shaking, and annual risk of failure. Components and systems are grouped by 1) isolation system, 2) superstructure and substructure, 3) systems and components, 4) umbilical lines that cross the isolation interface, and 5) hard stop or moat. The required performance of these components and systems under design basis earthquake (DBE) and beyond (extended) design basis shaking (BDBE) shaking is described and the rationale presented.

Seismic demands are calculated for DBE and BDBE shaking. Results of DBE analysis are used for a) calculating design loads on the superstructure, b) generating in-structure response spectra for design of SSCs, and c) establishing displacements for production testing of isolators.

Results of BDBE analysis are used to a) select the required clearance to a physical stop or displacement restraint, and b) establish displacements and forces for prototype testing of isolators. A stop, which may be a moat wall, is used to prevent excessive displacement of the isolation system and removes the isolation system from accident sequences involving earthquake shaking.

The paper describes the analysis and design procedures that can be used to implement a seismic isolation system in a safety-related nuclear structure. Emphasis is placed on the analysis of the isolation system, soil-structure interaction, risk-based performance objectives; and prototype and production testing of seismic isolators.

# Seismic isolation of reactor assembly for a fixed base ADS reactor building

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In the SILER Project it is interesting to apply seismic isolation technology for the Reactor Assembly of the fixed base Reactor Building for Acceleration Driven System Heavy Liquid Reactor (ADS MYRRHA) which contains the most critical safety related components such as Reactor Vessel, Safe Shutdown and Control Rod mechanisms, Primary Heat Exchangers, Primary Pumps, Spallation Target Assembly, and Fuel Assemblies, etc.. This paper presents the preliminary analysis results of the isolated Reactor Vessel and compares these with those of seismic isolated ADS Reactor Building. Some issues of the application of the seismic isolation of the ADS Reactor Assembly and further study on the partial seismic isolation application of the critical safety components will be discussed.

# Development of Pipe Expansion Joint for isolated LFR/ADS

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ADS System
Based on the expected maximum displacements for OBE and DBE, BOA BKT GmbH has identified the necessary physical properties of the piping joints and its orientation in the beam-line for RB Isolation and will present the kinematic seismic behavior of the system.

LFR System
Based on the expected maximum displacements for OBE, DBE and BDBE, BOA BKT GmbH has identified the necessary physical properties of the piping joints for the Main Steam (MS) and Feed-water (FW) piping.

BOA has analyzed the manufacturing requirements and will present simulations of the bellows hydro-forming process as well as a dynamic, natural mode FEA of the bellows.

# Development of Fail Safe system for isolated LFR & ADS

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In the last years, several extremely violent earthquakes occurred all over the world as, for example, the Niigata-Chuetsu-Oki earthquake (Japan, 2007), the Wenchuan earthquake (China, 2008), those which strongly struck Haiti and Chile in 2010 and that near the east coast of Honshu, Japan (March 11, 2011), which also caused devastating tsunami. These earthquakes were well higher than the expected design event (beyond design) and some of them struck large nuclear plants. Thus, the lesson learned from these events is that the demand for seismic capacity often exceeds our current regulations by a factor of 2 or even more. This implies that enhanced design solutions and methodologies, like base isolation, will gain considerable importance. This requires a new attention to the general layout of the plant in order to give adequate protection not only to the reactor core and vessels, but also to all the systems directly or indirectly related to safety to avoid situations like that recently occurred for the Fukushima plants.

The WP5 of the SILER project is dedicated to all those interface components connecting the isolated and non-isolated parts of the plant (i.e. pipelines), or components requiring a specific design in case of isolation of the system (i.e. cover joint of the seismic gap, pipe expansion joints, foundation and isolated concrete slabs, horizontal fail safe system etc.). The latter is the subject of this paper. As a matter of fact, even in case of beyond design earthquakes, the isolators shall never lose the capability of supporting the vertical load. Thus, the adoption of a horizontal fail safe system to limit the isolator deformation must be foreseen. It is also strongly recommended that the fail safe system includes some shock absorber (for example a rubber bumper) to soft the hammering between the isolated building and the foundation in case of extreme violent earthquakes. These devices are not present in the Cruas, Koeberg and Jules Horowitz Reactors, and are seldom used in civil buildings.

Thus, these devices will be designed taking into account two basic functions: to limit the isolator maximum displacement in case of beyond design events and to reduce the forces caused by the possible impact on them.

Initially, studies will consider the use of commercial marine fenders to evaluate whether the masses and forces involved are in the range of applicability of these devices. If not, other solutions will be investigated. The study will consider first the ELSY reactor and then the conclusions will be extended to MYRRHA.

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