Seismic-Initiated events risk mitigation in LEad-cooled Reactors: the SILER Project

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SUMMARY
SILER is a Project, partially funded by the European Commission, aimed at studying the risk associated to seismic-initiated events in Generation IV Heavy Liquid Metal reactors and developing adequate protection measures. The attention is focused on the evaluation of the effects of earthquakes (with particular regard to *beyond design* seismic events) and to the identification of mitigation strategies, acting both on structures/components design as well as on the development of seismic isolation devices, which can also have positive effects on economics, leading to an high level of plant design standardization. Attention is also devoted to the identification of plant layout solutions able to avoid risks of radioactive release from both the core and other structures (i.e. the spent fuel storage pools). Specific effort is devoted to the development of guidelines and recommendations for addressing the seismic issue in next generation reactor systems.

Keywords: Seismic isolation, Nuclear reactors, Lead cooled rectors

1. INTRODUCTION

The latest violent earthquakes that struck Japanese nuclear power plants (in particular Kashiwazaki-Kariwa in July 2007 and Fukushima in March 2011) renewed international focus on the structural strength of nuclear facilities. This has forced the nuclear engineering community to concentrate a significant research effort in the evaluation and mitigation of risks associated to earthquakes. In this contest, the SILER Project has been developed and then accepted and funded by EURATOM in 2011, within the Seventh Framework Programme. SILER is a Collaborative Project aimed at studying the risks associated to seismic initiated events in Gen IV Heavy Liquid Metal reactors and developing adequate protection measures. The attention is focused on the evaluation of the effects of earthquakes, with particular regards to unexpected (*beyond design*) events, and to the identification of mitigation strategies like seismic isolation, acting on both structures and components design.
The SILER Consortium is composed by ENEA (Coordinator, Italy), AREVA (France), SCK•CEN (Belgium), FIP Industriale (Italy), MAURER-SOEHNE (Germany), JRC (Ispra, Italy), SINTEC (Italy), KTH (Sweden), BOA (Germany), IDOM (Spain), ANSALDO (Italy), IPUL (Latvia), NUMERIA (Italy), VCE (Austria), SRS (Italy), CEA (France), EA (Spain) and NUVIA (France).
The Project deals with both Lead Fast Reactors (LFR) and Accelerator Driven Systems (ADS). In particular, reference is made to ELSY (§ 2, Alemberti et al. 2009 and 2010) and MYRRHA (§ 3, De Bruyn et al., 2010) concepts, respectively.

2. ELSY

The European Lead Fast Reactor is being developed starting from September 2006, in the frame of the ELSY project sponsored by the Sixth Framework Programme of EURATOM. The project, coordinated by Ansaldo Nucleare, involves a wide consortium of European organizations. The ELSY reference design is a 600 MWe pool-type reactor cooled by pure lead (see Fig. 1). The ELSY project demonstrates the possibility of designing a competitive and safe fast critical reactor using simple engineered technical features, whilst fully complying with the Generation IV goal of sustainability and minor actinide burning capability.

Sustainability was a leading criterion for option selection for core design, focusing on the demonstration of the potential to be self sustaining in plutonium and to burn its own generated minor actinides. To this end, different core configurations have been studied and compared. Economics was a leading criterion for primary system design and plant layout. The use of a compact and simple primary circuit with the additional objective that all internal components be removable, are among the reactor features intended to assure competitive electric energy generation and long-term investment protection. Low capital cost and construction time are pursued through simplicity and compactness of the reactor building (reduced footprint and height). The reduced plant footprint is one of the benefits coming from the elimination of the Intermediate Cooling System, the low reactor building height is the result of the design approach which foresees the adoption of short-height components and two innovative DHR systems. Among the critical issues, the impact of the large mass of lead has been carefully analyzed, notwithstanding it has been demonstrated that the effects given by the high density of lead can be mitigated by more compact solutions and improvement of the design of the Reactor Vessel support system (i.e. the adoption of seismic isolators for a full seismic-resistant design).

A more detailed description of the ELSY project and its main results is provided by Alemberti et al. (2009). The project ended in 2009 but the development of the ELSY reactor continued in the LEADER (Lead-cooled European Advanced Demonstration Reactor) project2 which has been funded in the 7th Framework Program.

Some partners of ELSY and LEADER also participate in SILER and cooperate to provide the input data to allow the design of the seismic isolation system and the related interface components. Thus, in the framework of SILER, a complete seismic analysis of ELSY in both isolated and fixed base conditions will be carried out. The aim is to evaluate the effects (and the benefits) of the adoption of seismic isolation on the behavior of the most critical components like the tank and its supports.

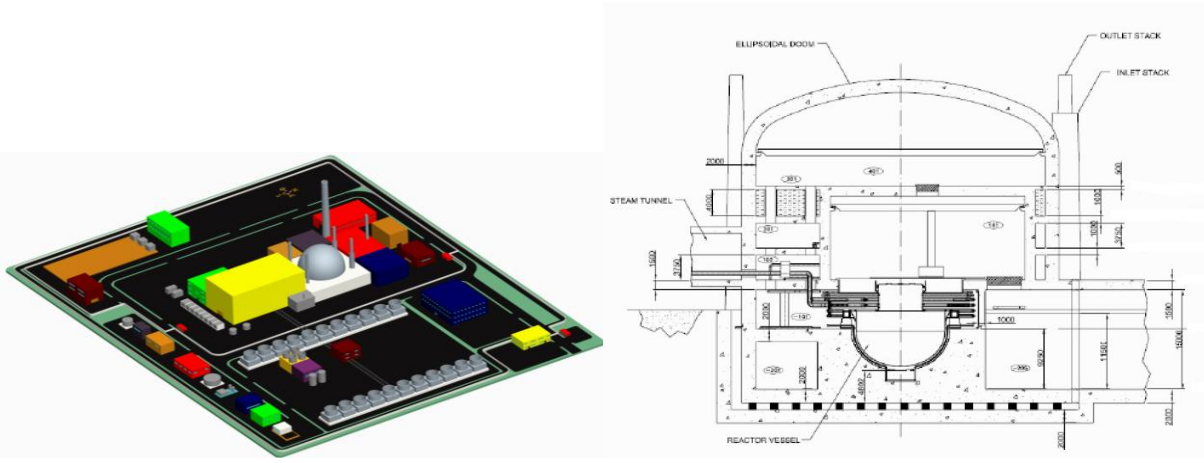

Figure 1. Sketch of the ELSY plan layout and lateral view of the reactor building with seismic isolation.

3. MYRRHA

MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) is the flexible experimental accelerator-driven system (ADS) in development at SCK•CEN in replacement of its material testing reactor BR2. A sketch of the plant is shown in Fig. 2. The Belgian Federal government has approved early 2010 the funding of this international project, which from 2023 onwards, will contribute to the development of innovative solutions in the field of nuclear technologies.

SCK•CEN, in association with 18 Europeans partners from industry, research centers and academia, responded to the Seventh Framework Programme call from the European Commission to establish a Central Design Team (CDT) for the design of a FAst Spectrum Transmutation Experimental Facility

(FASTEF) able to demonstrate efficient transmutation and associated technology through a system working in subcritical and/or critical mode. The project has started on April 1st, 2009 for a period of three years. Some partners of CDT also participate in SILER and cooperate to provide the input data to allow the design of the seismic isolation system and the related interface components. Thus, in the framework of SILER, as done for ELSY, also for MYRRHA a complete seismic analysis in both isolated and fixed base conditions will be carried out. The aim is to evaluate the effects (and the benefits) of seismic isolation on the behavior of the most critical components like the tank and the proton beam. More information about MYRRHA is provided by De Bruyn et al. (2010).

Figure 2. Lateral view of the MYRRHA building and detail of the tank-proton beam coupling.

4. SEISMIC ISOLATION OF NUCLEAR PLANTS

4.1. Application to Light Water Reactors

The first application of seismic isolation to a nuclear power plant (NPP) was completed at Cruas, France, where 4 PWRs (with a total electric power of 3600 MWe) were isolated at the end of the ‘70s (the construction began in 1978 and the reactors became operative between 1983 and 1984). The choice of seismic isolation was done to keep the design unchanged with respect to other reactors already designed or built by EdF in France, in places with lower seismicity (typically 0.2 g peak ground acceleration, being 0.3 g that of Cruas). For the same reason, two 900 MWe PWR units (same model of Cruas), were provided with seismic isolation at Koeberg, South Africa (30 km north of Cape Town). The construction began in 1976 (even before than Cruas) but the reactors were completed in 1984-1985. It is worth noting that the first new application after Cruas and Koeberg is represented by the Jules Horowitz Reactor, now under construction at the Cadarache Nuclear Centre site (France) with an isolation system composed by 195 neoprene bearings (900x900x181 mm size, manufactured by NUVIA, Freyssinet Group) already installed.
In addition, the ITER (International Thermonuclear Experimental Reactor) is going to be erected with base isolation, again at the Cadarache site. Among new water reactor designs, the IRIS (International Reactor Innovative and Secure) and the 4S (Super Safe, Small and Simple) reactor, developed by Toshiba-Westinghouse, must be cited. It is worth noting that for the IRIS, lot of activities on seismic isolation, even experimental, have been carried out, especially by the Italian partners of the consortium (see Forni et al., 2009 and Bergamo et al., 2011).

4.2. Application to Liquid Metal Reactors

The studies carried out up to now have shown as the issue of seismic protection of the plant is particularly felt in Liquid Metal systems. Compact pool-type designs of liquid metal cooled systems,

in fact, alleviate plant construction costs, at the same time compactness can introduce new safety issues. For the lead-cooled concepts, seismic design challenges are specifically related to the large mass of lead. Moreover, peculiar to a LFR design, besides the high density of the coolant, is the integration of the steam generators or heat exchanger equipment inside the reactor vessel: this implies the risk of a large potential load in the case of an earthquake and of a new load brought about by the Steam Generator Tube Rupture (SGTR) or Heat Exchange tube rupture accidents.
At now, several studies have been carried out.
The ALMR (Advanced Liquid Metal Reactor) is a sodium reactor developed by General Electric-Hitachi Nuclear Energy in the 80's; the project was sponsored by U.S. Department of Energy (DOE). The ALMR isolated structural configuration consists of a stiff steel-concrete box structure, which supports the reactor vessel, the containment dome, and the reactor vessel auxiliary cooling system stacks. The total isolated mass is about 230,000 kN, supported by 66 high damping rubber bearings made of hard compound (shear modulus G = 1.1 MPa). The Safe Shutdown Earthquake (SSE) is characterized by an horizontal and vertical peak ground acceleration (PGA) of 0.5g. The horizontal isolation frequency is 0.7 Hz, and the vertical frequency is greater than 20 Hz. ENEA participated in the verification of the design of the isolators.
The S-PRISM (Power Reactor Innovative Small Module) is a modular reactor (415 MW for each module), again developed by GE in the 80's. Of course, for this kind of reactor the standardization of the design is a very critical issue. Seismic isolation was considered the most promising solution to keep the design unchanged independently of the construction site. The reactor module was supported by 20 HDRBs which give to the system an horizontal frequency of 0.7 Hz and provide a reduction of the horizontal shear forces by a factor 3. The PGA was 0.5 g at the SSE. It is worth noting that this project was abandoned in 1994 before obtaining the licensing and now a new design, including seismic isolation, is in progress and aims to satisfy the severe requirements of GEN IV reactors.
For the STAR-LM (Secure Transportable Autonomous Reactor-Liquid Metal) reactor, now under development at the Argonne National Laboratory (ANL), the standardization of the design is a key issue even more important than for S-PRISM, also due to the severe requirements of GEN IV for lead reactors. The SSE and OBE are characterized by a PGA of 0.3g and 0.2 g, respectively. The isolation system is made of cylindrical isolators with a diameter of 1.2 m and a rubber height of 0.5 m; the isolation frequency is 0.5 Hz in the horizontal direction and 21 Hz in the vertical one. For this reactor, a study for seismic isolation in the vertical direction (with a frequency of 1.1 Hz) is being carried out.
The KALIMER (Korea Advanced LIquid MEtal Reactor) is an economically competitive, inherently safe, environmentally friendly, and proliferation-resistant sodium cooled reactor which is now being developed by the Korea Atomic Energy Research Institute. A total of 164 HDRBs (1.2m diameter) are installed between the ground and the lower base mat in the KALIMER-600 reactor and fuel handling buildings. The seismic gap between the isolated reactor building and the non-isolated wall is about 1.2 m, sufficient to avoid contacts ("hammering") even when the plant is subjected to a beyond design earthquake with a peak ground acceleration of 1.0 g.
The ESFR (European Sodium Fast Reactor) is under development in the framework of the European Collaborative Project CP-ESFR, with the aim of evaluating pros and cons of the loop and pool solutions. In this project, ENEA is responsible of the task *Design measures for consequence mitigation of seismic loads*, in the framework of which the seismic isolation of the whole reactor building has been proposed. Aim of the task is also the development of guidelines and recommendations to provide techniques and methods for the reduction of seismic vulnerability.
More information about seismically isolated NPPs is given by Forni, Poggianti and Dusi (2012).

5. SILER PROJECT MAIN ACTIVITIES

5.1. Development of Seismic Isolators

The main goal of SILER is the development and experimental qualification of seismic isolators for lead-cooled reactors. Two device typologies are considered in the Project: High Damping Rubber Bearings (HDRB, Fig. 3 left) and Lead Rubber Bearings (LRBs, Fig. 3 right).

HDRBs are composed by alternate rubber layers and steel plates, bonded together during the vulcanization phase of the isolator. The capacity of supporting the axial (vertical) forces is given by the reinforcing steel plates which hinder the radial deformation of the rubber. Horizontal (shear) deformations are allowed by the elasticity (or, better, hyper-elasticity) of the rubber, that also provides the restoring force. The shear modulus (G) of the rubber ranges between 0.4 MPa (soft compound) to 1.4 MPa (very hard compound). For civil building applications, a medium compound (G=0.8 MPa) is often used. For nuclear applications, due to the large masses to be isolated (and, consequently, the high stiffness needed), the hardest compound is often necessary. In this case, particular attention must be paid to the bonding between rubber and steel. Finally, the energy dissipation is obtained by using suitable chemical components in the rubber compounds; the equivalent viscous damping can range from 5% (natural rubber) to 15% (high damping rubber). It is worth noting that higher is the damping factor, lower is the failure limit of the isolator. Typically, natural rubber and high damping rubber fail beyond 500% and 300% shear strain, respectively. If higher damping values are needed, the use of lead rubber bearings is recommended instead of additional energy dissipaters.

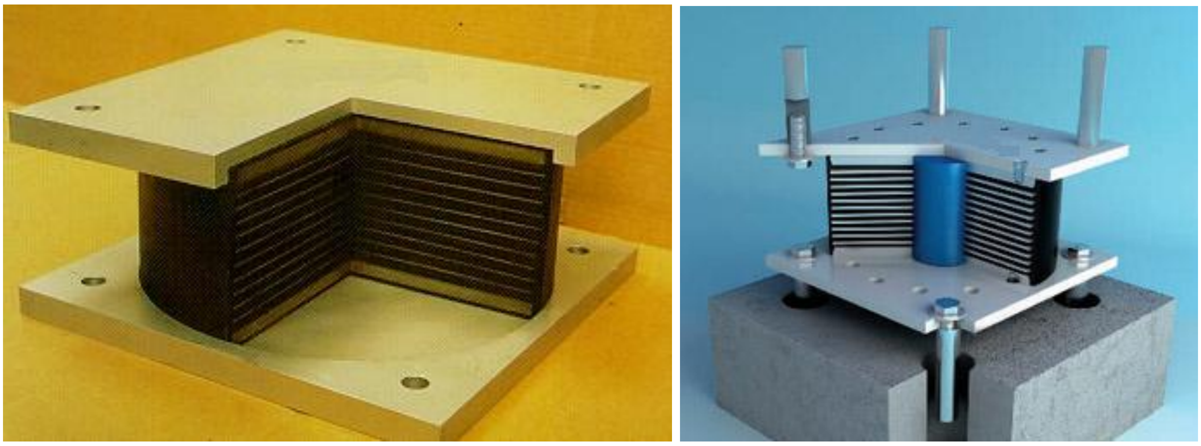

Figure 3. Sample of High Damping Rubber Bearing (left) and Lead Rubber Bearing (right)

Figure 4. Medium-size seismic isolator for civil application during a type test (compression plus one-directional shear loads applied al low velocity, according to the present standards). In the SILER project, large-scale isolators developed for nuclear plants will be qualified in three-directional dynamic conditions up to failure.

The isolators used for nuclear applications are usually quite large, due to the high mass of the superstructure. This introduce difficulties in the manufacturing process. In fact, the abovementioned vulcanization phase requires a quite uniform temperature distribution in the whole isolator, which is more difficult to be obtained for large volumes. Thus, particular attention must be paid to the production process controls and in the qualification of the device.

The insertion of one or more lead cores within a rubber bearings can increase the equivalent viscous damping of the isolator up to 25-30% (LRBs). The advantage to dissipate energy trough the lead core is that the isolator can be made in low damping natural rubber, which is more resistant to failure, as stressed above. The disadvantages are a more difficult manufacturing process and a lower re-centring capability.

The isolators developed in the SILER Project will be tested in full-scale and real three-directional dynamic conditions up to failure, with the aim of carefully evaluating the safety margins in case of *beyond design* earthquakes. It is worth noting that this test procedure is not required for civil constructions (Fig. 4) and was never used for nuclear applications.

A preliminary design of the seismic isolation system made of HDRBs has been completed for both ELSY (Fig. 5) and MYRRHA (Fig. 6) using finite element models. In both cases, seismic isolation has been applied to the whole nuclear island.

Isolators have been designed to reach 100% shear strain at the design displacement, including a multiplicative factor 1.2 and taking into account a 5% eccentricity effect, as required by EN15129 (see § 5.3). This allows to have significant safety margins (200-300%) against failure or instability in case of *beyond design* events. Moreover, in the range around 100% shear strain (say 75%-125%), the stiffness of the isolator assumes the minimum value and is relatively constant.

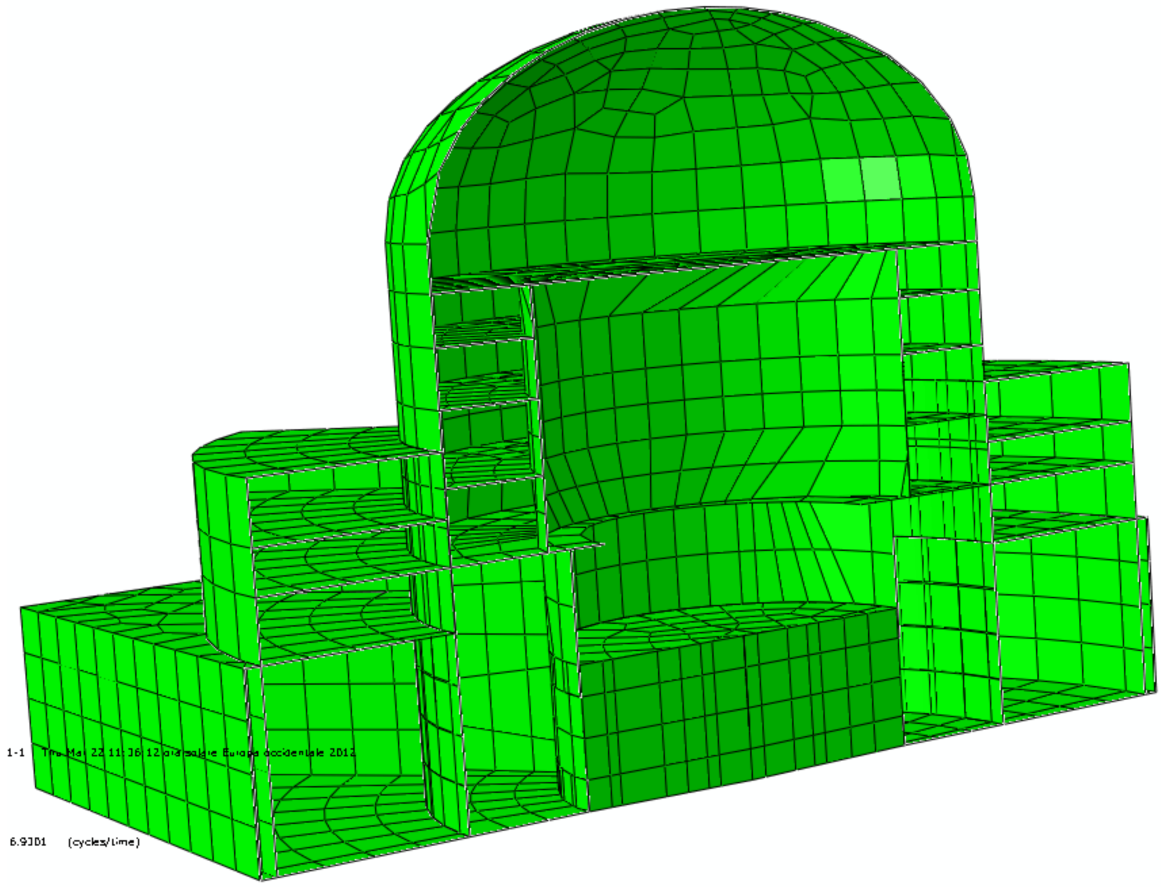

Figure 5. Finite Element Model of ELSY used for the preliminary design of the seismic isolators.

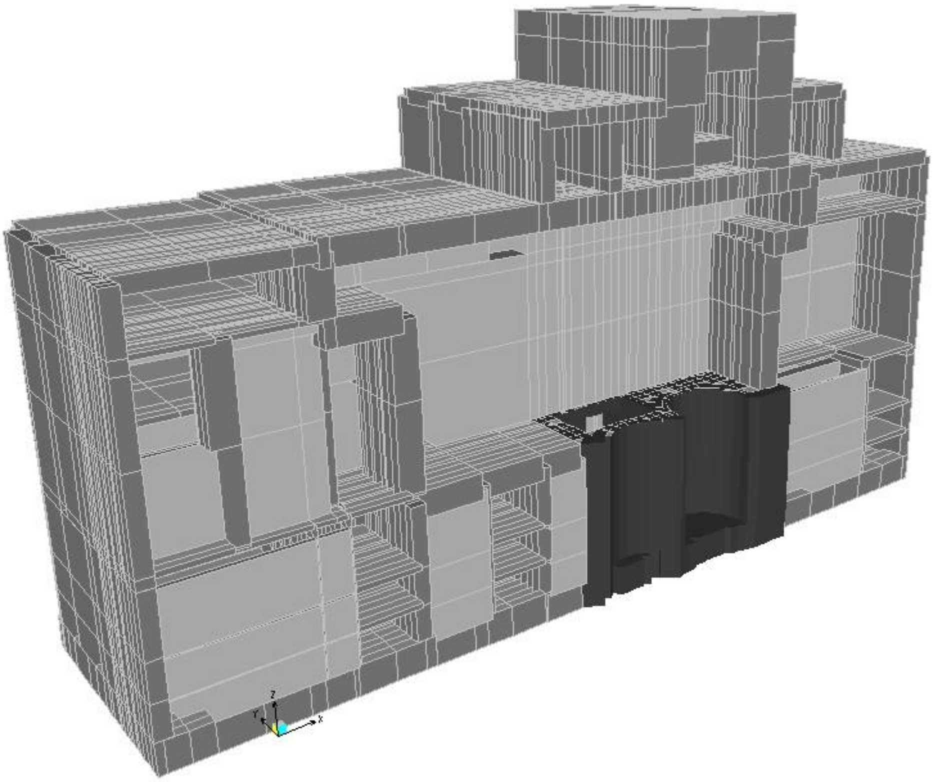

Figure 6. Finite Element Model of MYRRHA used for the preliminary design of the seismic isolators.

5.2. Interface Components

The adoption of base isolation introduces significant relative displacements between the isolated and non isolated parts of the plant. Thus, a seismic gap must be present all around the isolated part and shall be adequately protected and kept free during the whole life of the structure, in order to allow the relative movements in case of earthquake. All the service networks and pipelines crossing the seismic gap shall be provided with suitable expansion joints.

5.2.1. Seismic Gap

The seismic gap shall be covered with a weatherproof joint capable not only to absorb bi-directional horizontal displacements in case of earthquake, but also to avoid infiltrations of water in the room where the isolators are installed (not only in case of rain and snow, but also for floods and tsunamis). The seismic joint protection must also be fireproof. In fact, in case of airplane crash, some burning fuel can reach the gap; in this case it’s necessary to avoid that it reaches the isolators. Moreover, some wreck of the plane can fall over the cover gap; thus, it shall be adequately protected or designed to resist to the impact. The seismic gap cover will developed by MAURER SHOENE and will be tested on the ENEA shaking table in three-directional conditions.

5.2.2. Expansion Joints

For the regular service networks (pipes, wires and cables) several kind of expansion joints are already available on the market, used in the isolation of civil buildings, and no particular design solutions are necessary for applications in nuclear plants. When the whole nuclear island is isolated, one of the most critical systems crossing the seismic gap is the pipeline which goes to the turbines (containing hot and pressurized steam). Expansion joints similar to those needed in this case were tested in the framework of the INDEPTH project for an isolated tank of a petrochemical plant (see Fig. 7 and ENEL.Hydro et al., 2002).

The technology for this kind of devices already exists also for high temperatures and pressure. It is worth noting that a smart disposition of two gimbals and one angular joints along the pipeline (with two 90° curves, at least) provide 6 degree of freedom to the system and can accommodate even huge displacements with very limited rotations (and then stresses) of the joints. The expansion joints will be developed by BOA and tested in pseudo-dynamic conditions up to large displacement by JRC of Ispra.

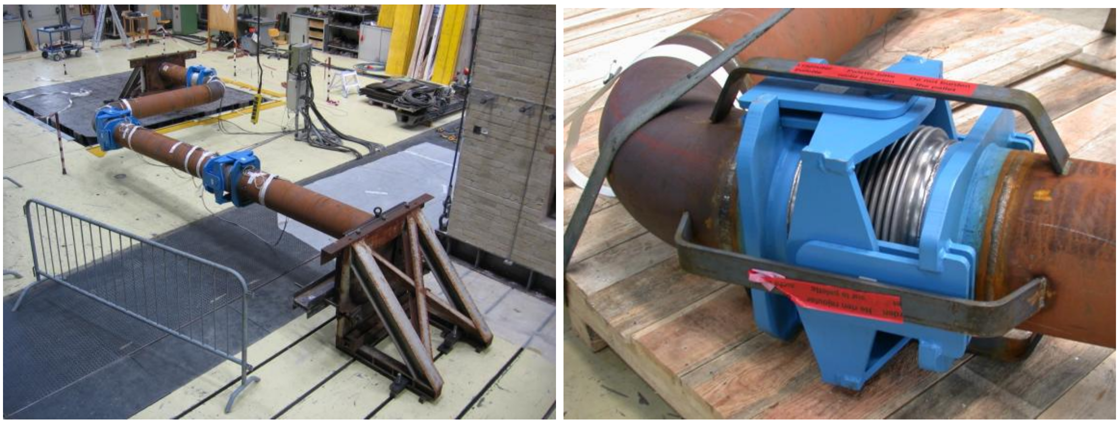

Figure 7. Pipeline expansion joints (ambient temperature and pressure) used for seismically isolated tanks in petrochemical plants. In SILER, similar devices will be developed and tested in full scale for the hot and pressurized steam pipeline crossing the gap between isolated and conventionally founded part of the plant.

5.2.3. Horizontal fail safe system.

Even in case of beyond design earthquakes, the isolators shall never lose the capability of supporting the vertical load. Thus, the adoption of an 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. These devices, which are not present in the Cruas, Koeberg and Jules Horowitz Reactors, and are seldom used in civil buildings (Fig. 8), will be designed by NUMERIA and ENEA.

It is worth noting that, to optimize the distance between the base slab of the isolated building and the bumper, it is necessary to know the real failure (or instability) limit of the isolator. As stressed above, this can be done only performing three-directional tests on full scale prototypes. To provide an adequate safety margin to the deformation of the isolator, it is recommended that the rubber shear strain at the design displacement at DBE (Design Basis Earthquake) don not exceed 100% (this limit is 250% for civil applications).

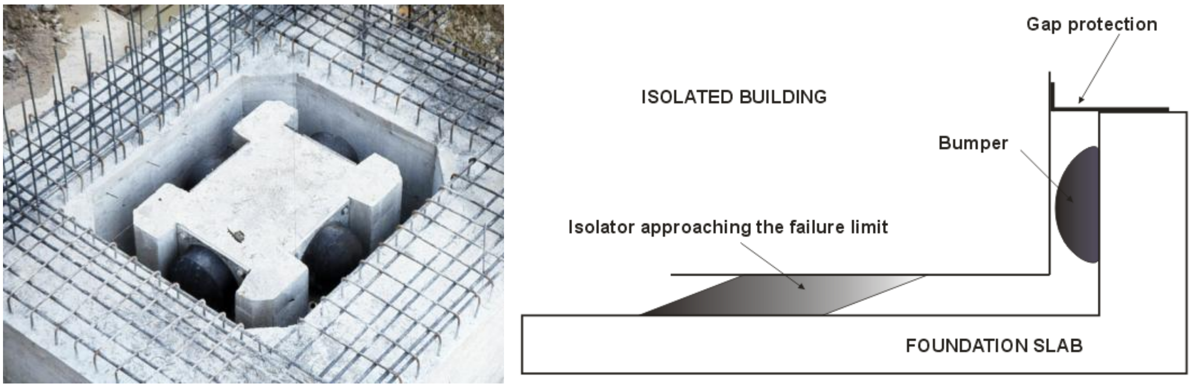

Figure 8. The horizontal fail safe system of the Telecom Italia Centre of Ancona (Italy) and related working sketch. In seismically isolated NPPs, the possibility of exceeding the isolator failure limit shall be eliminated by using suitable devices able to limit the maximum deformation and damp the shock between building and lateral foundation wall in case of beyond design earthquakes.

5.3. Guidelines and standardization procedures

Aim of SILER is also the development of a proposal of guidelines for the design, qualification, in-service inspection, maintenance and replacement of isolators in nuclear power plants.
The design and construction of nuclear plants are regulated, all over the world, by well known standards (issued by the NRC, IAEA, JAEA, etc.) that also include the seismic conventional design, but without seismic isolation. Moreover, there are several standards for the design and construction of isolated civil buildings like EUROCODE 8 and others. Finally, there are some standards addressed to the design, manufacturing and testing of seismic isolators for civil applications, like EN 15129, which came into force in 2010 in all European countries. But no standard, at present, is specifically addressed to seismically isolated nuclear reactors or to isolators to be used in such plants (apart the Japanese *Design and Technical Guideline of Seismic Isolation Structure for Nuclear Power Plant-JEAG 4614-2000*, that, unfortunately, as far as the authors know, is available in Japanese, only).
The lack of existing specific standards is one of the most important problems in the application of seismic isolation to nuclear plants, especially for what concerns the qualification of the isolators. New guidelines and/or recommendations are necessary to regulate the qualification of these very critical components, maybe developed starting from the existing ones.
EN15129 became mandatory in August 2011 in all European countries for any kind of application where seismic isolators are used. However, it is not specifically addressed to nuclear plant. Thus, EN15129 can be used as a sort of *minimum requirement* in nuclear applications and improvements shall be done. To this aim, some activities are foreseen in SILER, for showing that EN15129 is basically suitable for applications in nuclear plants but with some, not always minor, improvements (Forni et al., 2012).

5.4. Dissemination of information

In SILER, a whole work package is aimed at the dissemination and external communication, with the main objective to enhance the diffusion of knowledge and information thanks to the exploitation of the potentialities of the new information technologies as well as using conventional tools.
Most of the deliverables produced within the project will not be confidential and will be published on the project website (www.siler.eu).
Particular attention is dedicated to the dissemination of information to young generations of scientists through a specific training course held in Verona on 21-25 May 2012. Moreover, four PhD thesis are already started on specific issues.
Finally, an International Workshop will be organized at the end of the project where PhD students participating in the program can presents the results of their activity.

6. CONCLUSIONS

The paper presented the main features of the SILER Project together with a short description of the ELSY and MYRRHA systems and the world state-of-the-art of seismically isolated nuclear reactors (included new designs), focusing on the main problems encountered in the application of this technology to lead reactors, such as the need of manufacturing and testing very large isolators and to design interface components capable of absorbing large displacements, and the lack of standards specifically addressed to isolated nuclear reactors.
It is recognized that for HLM-cooled reactors the seismic risk mitigation is a key issue to be addressed for the development of such systems and to guarantee their operability in safe conditions.
In general, it can be stressed that:

- All the present applications or recent new designs of isolated NPPs use rubber isolators (with or without lead plugs) acting in the horizontal directions only. These devices are the best candidate to isolate nuclear plants.
- The isolation in the vertical direction of the whole nuclear island is not possible, yet; at present, if necessary, this kind of protection shall be limited to some critical components and equipments through suitable energy dissipaters (spring-dashpot devices).

- The technology for pipe expansion joints connecting the isolated part of the plant with the conventionally founded one, is almost already available, but requires some improvements.
- The adoption of an horizontal fail-safe system is strongly recommended, to avoid the isolator failure or instability in case of extremely violent earthquakes (*beyond design*).
- EN15129 can be used as reference standard for the design, qualification, in-service inspection, maintenance and replacement of isolators. However, since this standard is not specifically addressed to NPPs, EN15129 shall be used as a sort of "*minimum requirement*" and some improvements shall be done.

The SILER Project deals with the most critical issues related to the seismic isolation of lead-cooled reactors and will certainly provide significant improvements with respect to the present state-of-the-art also by means of experimental campaigns on full-scale isolator (tested with dynamic three-directional excitations up to failure) and expansion joints.

ACKNOWLEDGMENTS

Authors warmly thank EC for the financial support to the SILER Project.

They also thank the partners of SILER who contributed to the preparation of this paper, in particular Didier De Bruyn and Bong Yoo (SCK•CEN) and Alessandro Alemberti (ANSALDO) for the MYRRAH and ELSY description, and Alberto Dusi and Alessandro Poggianti for the MYRRAH and ELSY modelling, respectively.

NOMENCLATURE

ADS: Accelerator Driven System
CDT: Central Design Team (of MYRRHA/FASTEF)
DBE: Design Basis Earthquake
DHR: Decay Heat Removal
ELSY: European Lead-cooled System
FASTEF: FAst Spectrum Transmutation Experimental Facility
GIF: Generation IV International Forum
HDRB: High Damping Rubber Bearing
HLM: Heavy Liquid Metal
LEADER: Lead-cooled European Advanced Demonstration Reactor
LFR: Lead-cooled Fast Reactor
LRB: Lead Rubber Bearing
MYRRHA: Multi-purpose hYbrid Research Reactor for High-tech Applications
NPP: Nuclear Power Plant
PGA: Peak Ground Acceleration
SGTR: Steam Generator Tube Rupture
SILER: Seismic-Initiated events risk mitigation in LEad-cooled Reactors
SNE-TP: Sustainable Nuclear Energy Technology Platform
SRA: Strategic Research Agenda

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