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SEISMIC-INITIATED EVENT RISK MITIGATION IN LEAD-COOLED REACTORS: MAIN RESULTS OF THE SILER PROJECT

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Abstract: This paper gives a general overview of SILER, a Collaborative Project funded within the 7th EC Framework Programme, aimed at studying the risks associated with seismic initiated events in Generation IV Heavy Liquid Metal reactors and developing adequate protection measures. In SILER, the attention is focused on the evaluation of the effects of earthquakes, with particular regard to unexpected (*beyond design*) events, and to the identification of mitigation strategies like seismic isolation.

Specific sections of the paper are addressed to the design, development and testing of the isolators (High Damping Rubber Bearings and Lead Rubber Bearings) and the most critical interface devices like flexible joints for pipelines and joint-cover of the seismic gap. These devices showed excellent behaviour during severe qualification tests in real dynamic conditions and confirmed the reliability of the seismic isolation technique.

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 concerns 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 with earthquakes. In this context, the SILER Project has been developed, accepted and funded by EURATOM within the 7th Framework Programme. The SILER project started in 2011 and has been concluded in September 2014.

SILER is a Collaborative Project aimed at studying the risks associated with 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 regard to unexpected (*beyond design*) events, and to the identification of mitigation strategies like seismic isolation. 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 (European Lead Fast Reactor, see § 2 and Alemberti et al., 2009, 2010) for LFR, and to MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications, see § 3 and De Bruyn D. et al., 2012) for ADS. For these reactors, seismic isolation systems made of High Damping Rubber Bearings (HDRBs) and Lead Rubber Bearings (LRBs) have been designed (§4), together with the related interface components (§ 5).

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Nowadays, only very few NPPs are base isolated: 4 PWR units at Cruas (France) and 2 identical PWR units at Koeberg (South Africa) built in the ‘80s, the Jules Horovitz Reactor and the ITER machine, under construction at the nuclear site of Cadarache (France). On the contrary, most of the new designs of innovative reactors of GEN IV foresee seismic isolation. SILER showed that this technique is reliable and already mature for a wide application in Nuclear Power Plants; furthermore it has been demonstrated that the existing technology only needs some minor improvements, especially in the field of the qualification of large isolators. It is worth noting that one of the reason for a so limited number isolated reactors is the lack of specific standards, especially in Europe and USA. To this aim, SILER implemented suitable guidelines for the design, manufacturing, testing, installation and maintenance of seismic isolators and interface components.

2. ELSY

The European Lead Fast Reactor is under development since September 2006, in the framework of the ELSY project, sponsored by the 6th Framework Programme of EURATOM. The project, coordinated by Ansaldo Nucleare, involved a wide consortium of European organizations. The ELSY reference design is a 600 MWe pool-type reactor cooled by pure lead (Figure 1). The ELSY project demonstrates the possibility of designing a fast critical reactor competitive and safe 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 aim, 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 shall be removable, is 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, and the low reactor building height is the result of the design approach which foresees the adoption of short-height components and two innovative Decay Heat Removal systems. Among the critical issues, the impact of the large mass of lead has been carefully analysed, 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, 2010. It is worth noting that the project ended in 2009, but the development of the ELSY reactor continued in the LEADER (*Lead-cooled European Advanced Demonstration Reactor*) project, which has been funded in the 7th Framework Program. Now, the demonstrator of the European Lead-cooled Reactor is ALFRED, whose development continues in the ESNII Plus (*Preparing ESNII for Horizon 2020*) project (see Poggianti et al., 2015) again funded in the 7th Framework Program.

Some partners of ELSY and LEADER projects 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, were carried out, with the aim of evaluating 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. For the purposes of the SILER activity, a Finite Element Model of the reactor building aimed at reproducing the general layout of the structures, their masses and centres of gravity was implemented in the ABAQUS code (Figure 2). The internal components, roughly modelled, mainly aimed at providing the correct mass distribution. The total mass acting on the isolation system is 1.36×10^8 kg, included the common basement. Two series of three-directional artificial acceleration spectrum compatible time-histories, generated by partner Empresarios Agrupados, were used in the analyses. The first tern was selected to be spectrum-compatible with the RG 1.60 (extended to the east coast, hard soils). The second one was selected to be compatible with the Eurocode 8 type 1, soil E (soft soils). The maximum PGA considered was equal to 0.3g in DBE (Design Basis Earthquake) conditions. Several parametrical analyses have been performed in order to design and optimize the isolators layout (§ 4.1). More information about this activity is given by Poggianti et al., (2014).

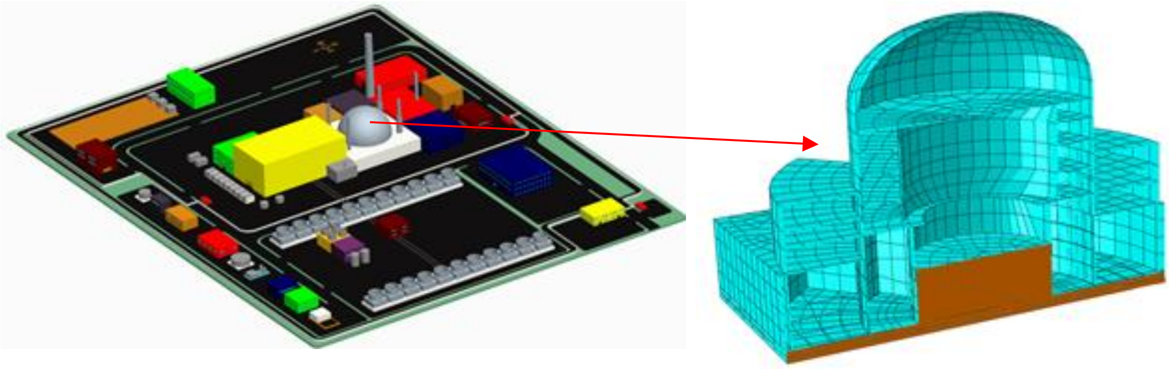

Figure 1. Sketch of the ELSY plant layout. Seismic isolation is applied to the whole reactor building.

Figure 2. Section of the ELSY reactor building FEM provided with base isolation.

3. MYRRHA

MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) is the flexible experimental Accelerator-Driven System (ADS) under development at SCK•CEN in replacement of its material testing reactor BR2. Figure 3 shows a sketch of the plant and its location in Mol (Belgium). The Belgian Federal Government has approved in 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 European partners from industry, research centers and academia, responded to the 7th 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 started on April 1st, 2009, and ran for a period of three years.

Some partners of CDT also participate in SILER and cooperate to provide the input data for the design of the seismic isolation system and the related interface components. Thus, as was done for ELSY, a complete seismic analysis in both isolated and fixed base conditions was carried out for MYRRHA. The aim was 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 De Bruyn et al., 2012.

In the framework of SILER, different Finite Element (FE) models have been implemented by NUMERIA in the MIDAS/Gen and SAP2000 NonLinear codes with the aim of carrying out sensitivity analyses and to define the optimal modeling for the foreseen seismic isolation system design. Figure 4 shows the FE mesh that has been used for the analyses that lead to the definition of the base isolation system (§ 4.2). The seismic input was the same used for ELSY (§ 2). More information about this activity is given by Poggianti et al., (2014).

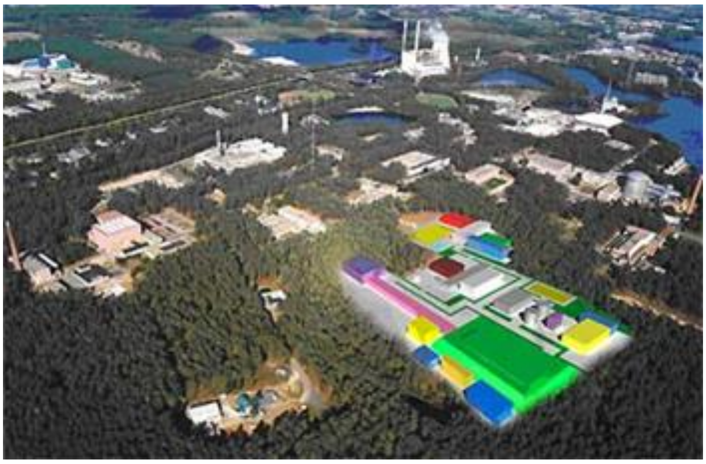

Figure 3. Sketch of the MYRRHA plant layout in the Mol site. Base isolation is applied to the whole reactor building (green).

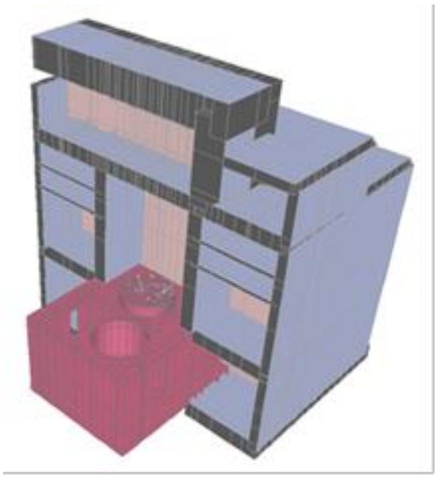

Figure 4. Section FEM of the MYRRHA reactor building (isolated).

4. Isolators

One of the main goals of SILER was the development and experimental qualification of seismic isolators for lead-cooled reactors. Two device typologies were considered in the Project: High Damping Rubber Bearings (HDRBs) and Lead Rubber Bearings (LRBs).

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, soft (G=0.4 MPa) or medium (G=0.8 MPa) compounds are 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. In effects, the higher the shear modulus, the higher the shear stress developed at the bonding surface, and the more critical the steel-rubber adherence, to which is related the failure in shear of the isolators. Finally, the energy dissipation in HDRBs is obtained by using suitable rubber compounds; the equivalent viscous damping can range from 5% (natural rubber) to 10-15% (high damping rubber compound).

The isolators used for nuclear application are usually quite large, due to the high mass of the superstructure. This introduces difficulties in the manufacturing process. In fact, the abovementioned vulcanization phase requires a uniform temperature distribution in the whole isolator, which is more difficult to obtain for large volumes. Thus, particular attention must be paid to the production process controls and to the qualification by tests of the full-scale device. The insertion of one or more lead cores within rubber bearings can increase the equivalent viscous damping of the isolator up to 25-30% (LRBs). The advantage of such high level of energy dissipation is the reduction of horizontal displacements, very important in areas with very high seismicity. The disadvantages are a more difficult manufacturing process, and a lower re-centering capability.

In the next paragraphs a short description of the isolators design for both ELSY and MYRRHA is provided. The results of the experimental campaigns performed for their qualification are described by Castellano et al., 2015.

4.1 Isolators for ELSY

The seismic isolation system proposed for the ELSY reactor is made of elastomeric isolators. Different configurations and isolation periods were analysed in order to optimize the dynamic response of the reactor building and its internals. Both HDRB and LRB solutions have been considered. The final isolation system was designed to obtain a natural period T_i = 1.75 s and an equivalent viscous damping of 10%. The system is composed of 225 (15x15 grid, Figure 5) HDRBs having a diameter of 1350 mm, a rubber height of 256 mm and an equivalent stiffness (Ke) of 7.83 kN/mm.

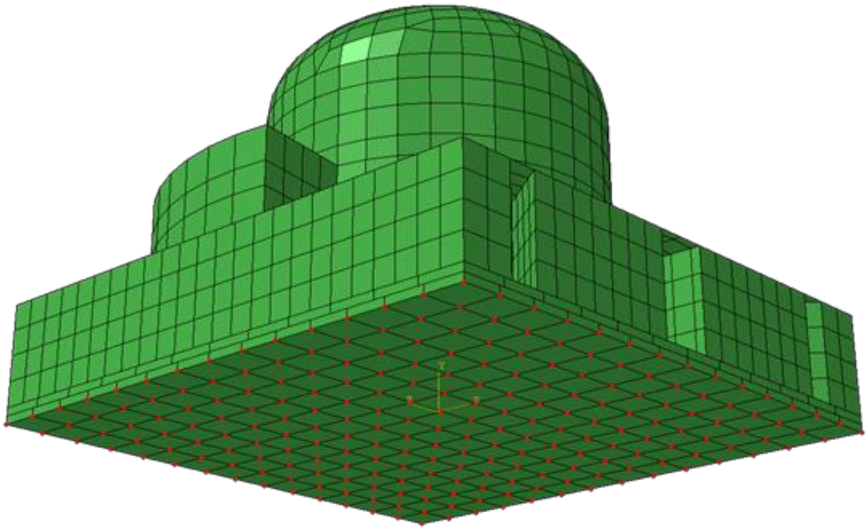

Figure 5. FEM of the ELSY reactor building and position of the isolators.

A bilinear model for the isolators was developed according to the FEMA 356 code, and then implemented in the FE model of the structure. The numerical analyses were performed using the ABAQUS code and the abovementioned acceleration time-histories (§ 2). The maximum deformation of the isolators and the maximum acceleration at the basement level, above the isolation system, calculated with the Design Basis Earthquake (PGA = 0.3 g) are reported in Table 1. It is worth noting that the maximum displacement is always lower than 100% shear strain.

Table 1. Maximum displacement (module) calculated for the ELSY HDRB at the design conditions.

Time-history	U1 (mm)	U2 (mm)	U max (mm)	A max (m/s^2)
RG t1	143	194	220	2.4
RG t2	121	163	176	2.4
RG t3	138	195	196	2.7
EC8 t1	107	182	190	2.6
EC8 t2	181	138	186	2.4
EC8 t3	223	144	251	2.9

Several scaled samples have been manufactured and tested by partner FIP Industriale. Moreover, a full-scale prototype has been tested on the SRMD (Seismic Response Modification Device) machine at the San Diego University (CA, USA) in real, three-directional seismic conditions up to failure, showing a very good behavior (Castellano et al, 2015).

3.1 Isolators for MYRRHA

The whole MYRRHA reactor building has been isolated by use of HDRBs or, alternatively, of LRBs (with the aim of reducing seismic displacements). The proposed isolation systems are made of an overall number of 339 elastomeric bearings of two types (see tables 2 and 3): 80 devices are of type A and 259 of type B. Figure 6 shows the disposition of the isolators.

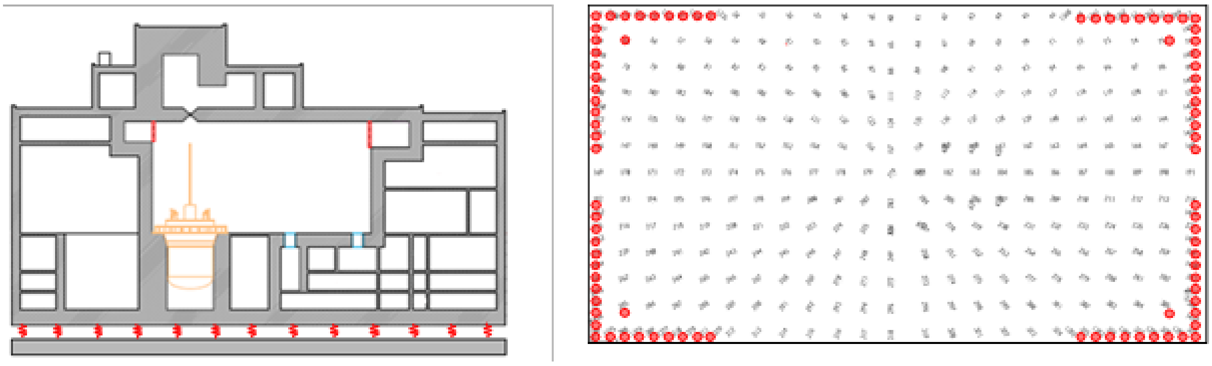

Figure 6. Layout of the isolation system for MYRRHA

Bearings types and locations were chosen so as to have a good coincidence between the centre of mass with the centre of stiffness. Bearings type A (in red in Figure 6) are placed at the slab corners (with a spacing of 2.0 m), while bearings type B are disposed according to the layout shown in figure 6 at an equal spacing of 4.0 m. Spacing has been defined taking into account construction procedures, as well as isolators maintenance and replacing needs.
As mentioned above, an LRB-based isolation option was considered in order to limit seismic displacements. LRBs are actually characterized by higher values of damping and stiffness than HDRBs, thus effectively contributing to earthquake induced displacements. It is, however, worthwhile recalling that when using devices with high values of damping, possible adverse effects of damping in seismic isolated structures have to be carefully considered. The effect of damping in higher mode response has been widely studied, and results are published in literature (Kelly, 1990; Politopoulos, 2008). The analyses carried out on the MYRRHA nuclear island confirmed that the isolators displacement and structural base shear may be reduced thanks to higher damping, but the floor accelerations are increased. Tables 2 and 3 summarize the main design parameters of type A and type B HDRBs and LRBs, respectively, as per the final design.

Table 2. HDRBs main parameters

	Type A	**Type B**
Plan size	Diam. 1600 mm	Diam. 1050 mm
Displacement at DBE d_{bd} (mm)	300	300
Horizontal stiffness (kN/mm) at d_{bd}	9.88	4.18
Equivalent viscous damping (%) at d_{bd}	10%	10%
Vertical stiffness (kN/mm)	8724	4229

Table 3. LRBs main parameters

	Type A	**Type B**
Plan size	1250 mm x 1250 mm	Diam. 900 mm
Displacement at DBE d_{bd} (mm)	161	161
Horizontal stiffness (kN/mm) at d_{bd}	16.43	4.81
Equivalent viscous damping (%) at d_{bd}	28.7	27.1
Vertical stiffness (kN/mm)	9105	3404

5. Interface devices

The adoption of base isolation introduces significant relative displacements between the isolated and conventionally founded parts of the plant. Thus, a seismic gap of suitable width shall surround the isolated part. Of course, it shall be adequately protected from bad weather (included floods) and other possible damage and kept free during the whole life of the structure, in order to allow for relative movements in case of earthquake (§ 5.1). Moreover, all the service networks and pipelines crossing the seismic gap shall be provided with suitable expansion joints (§ 5.2).

5.1 Joint cover

According to the design specification, the joint cover shall be:

1. weatherproof (against rain, snow and even flood)
2. fireproof (burning fuel could reach isolators in case of aircraft crash)
3. resistant to impacts (wreckage could fall on the joint cover)
4. able to accommodate all relative motions between reactor building and pit wall.

The width of the seismic gap is defined not only by the maximum displacement calculated for a beyond-design earthquake, but also by the need to allow access to the lower part of the reactor building for inspection, maintenance, replacement of isolators, etc. In the case of ELSY, the seismic gap is a sort of “tunnel” 2.4 m wide (see Figure 7). The design and manufacturing of the joint cover was the responsibility of partner MAURER. The concept solution accommodates all occurring DBE-displacements without any mechanical impact (i.e. the device remains fully operational after an earthquake of this category). Unfortunately, this feature cannot be maintained in beyond design conditions because the corresponding contraction is too high to be accommodated. A mechanical fuse is activated after 530 mm in contraction to avoid severe damage to the buildings. The fuse consists of commercial bolts that are sheared off. Further damage of the joint cover is not going to occur, since all adjacent components are markedly more robust than the bolts. The tapped threads are very likely to make an exception, but it’s certainly possible to fix with a repair-method, instead of discarding the whole device. The necessity of repair works after an earthquake of such intensity can hardly be avoided.

A full-scale segment of the joint cover has been manufactured and successfully tested in two-directional seismic conditions at the shaking table of ENEA (Figure 8). The test campaign demonstrated the full reliability of the device.

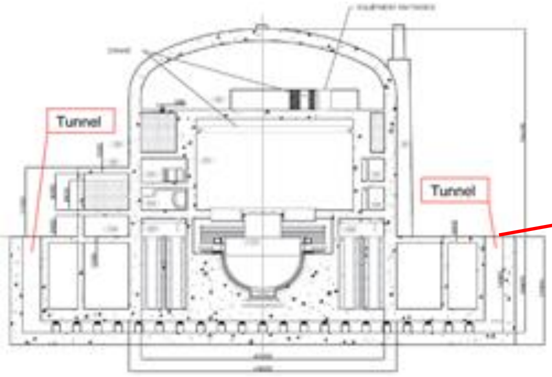

Figure 7. Seismic gap around the seismically isolated ELSY reactor building.

Figure 8. A full scale joint cover segment during shaking table tests at ENEA lab.

5.2 Flexible joints for pipeline

For the regular service networks (pipes, wires and cables) several kinds of expansion joints are already available on the market, used in the isolation of civil buildings; thus no particular design solutions are necessary for applications in nuclear plants, apart from the more severe qualification codes. However, when the whole nuclear island is isolated, one of the most critical systems crossing the seismic gap is the main steam pipeline (containing hot and pressurized steam) which connects the turbine building to the nuclear structure.

In the framework of SILER, partner BOA developed special Metal Bellows Expansion Joints capable of compensating for a 90 cm displacement (corresponding to the beyond-design earthquake). These joints are designed to be installed along the pipeline connecting the ELSY reactor building and the turbine island (Figure 9). Two gimbal joints are necessary to compensate for the horizontal movements. A third angular joint is necessary when the vertical displacements are significant (this is not the case with nuclear plants, due to the high

vertical stiffness of the isolators). Figure 10 shows a sketch of the expansion joint system designed for ELSY (two pin expansion joint system).
A full scale expansion joint was manufactured by BOA and tested by partner JRC Ispra on the reaction wall of the ELSA laboratory. The expansion joint was connected with two segments of pipeline in real size and under the service pressure (Figure 11). The results of this experimental campaign, which was in progress during the preparation of this paper, will be made available on the web site of SILER (www.siler.eu).

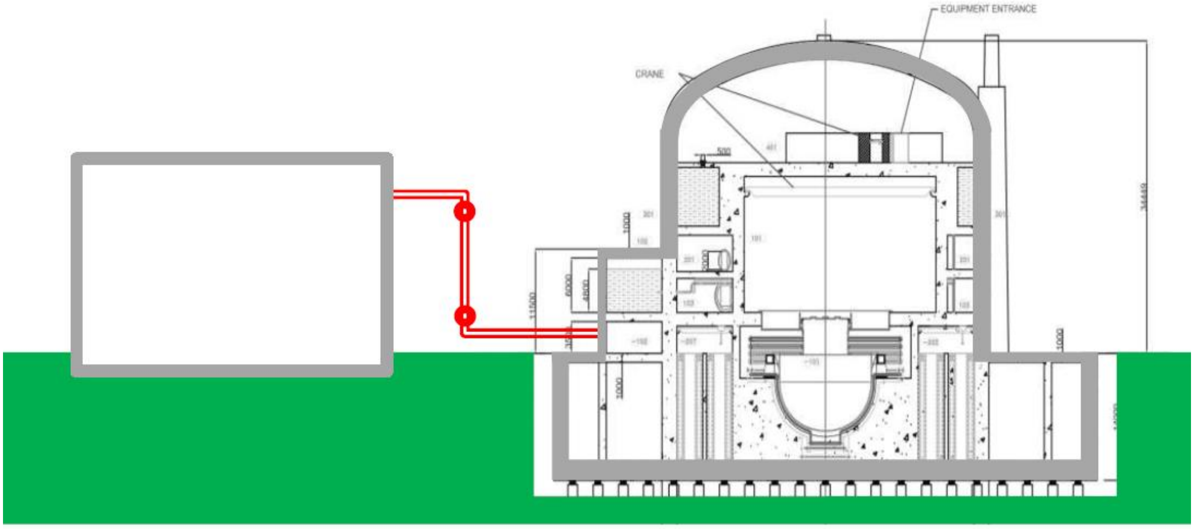

Figure 9. Sketch of the pipeline connecting the ELSY reactor building and the turbine island, provided with two flexible joints to adjust the horizontal displacement.

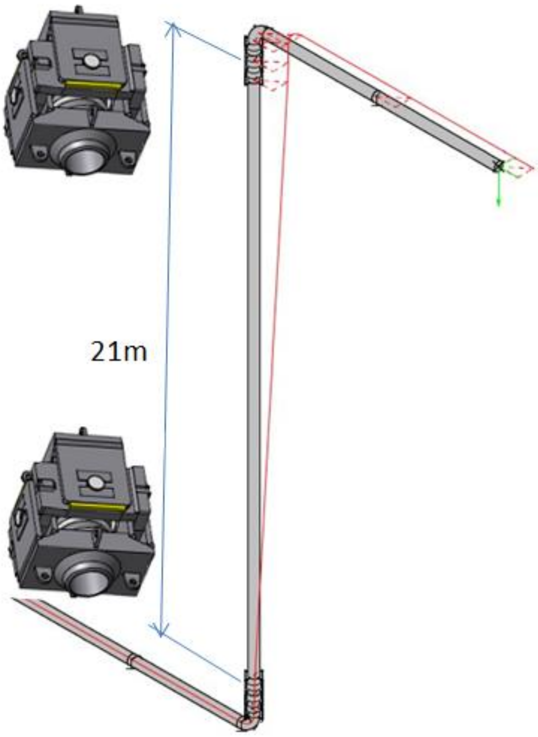

Figure 10: two pin disposition is needed to adjust horizontal movements.

Figure 11. The full scale joint during tests at the ELSA lab (curtesy of JRC Ispra).

6. Other SILER activities

In SILER, lots of numerical analyses have been performed, not only to design the isolators and devices described in the previous sections, but also to evaluate the effects of phenomena initiated by the earthquake (like sloshing) or associated with it (like tsunamis/flooding).

In WP3 (*Risk analysis for critical components*), risk of damage of components and structures due to seismic excitation has been evaluated, with particular regard to the sloshing phenomena, considered as key issue in HLM systems, due to the high density of lead and the related high inertial forces. Partners IDOM and KTH implemented detailed models of the studied reactors, and simulated the dynamic phenomena in which local equipment response could undergo significant coupling with the overall motion of the reactor. Particular attention has been paid to the fluid-structure interaction with the vessel and the risk of gas entrapment into the coolant. In the same WP, partner SINTEC performed the fragility analysis of the seismic isolator (the most critical component from the seismic point of view) which provided excellent results in terms of reliability.

In WP5 (*Interface components*), in addition to the joint cover and the flexible joints for pipelines previously described, the need of having horizontal fail safe systems for both the reactor concepts was evaluated. This device is, essentially, a shock absorber which limits the maximum displacement, and damps the contact force between the base slab and the lateral containment wall in case of extremely violent seismic events. It is worth noting that these events should occur only for beyond-design earthquakes having an intensity 3-4 times higher than the design value. The possibility of using marine fenders (already available on the market) or similar devices has been considered. More information about this activity is given by Poggianti et al., 2014.

One of the main advantages of seismic isolation is that it allows for the standardization of the design, making it almost independent of the seismicity of the construction site. Thus, in SILER, WP6 (*Recommendations for standardization*) was devoted to implementing recommendations and guidelines for mitigating the seismic risk through the adoption of seismic isolation. Attention was also paid to the evaluation of the benefits in terms of economics (derived from the mitigation of the failure risk related to earthquakes) and the knowledge transfer to Gen III LWR technologies.

In order to circulate and diffuse the scientific results reached in SILER, WP7 (*Dissemination of information*) was completely dedicated to dissemination and external communication. A large effort was dedicated to the implementation of a website (www.siler.eu), containing all the information on the project, as well as data, news, and general material considered of interest for the communities of civil and nuclear engineers, and scientists involved in the development of the next generation nuclear systems, with particular attention to safety aspects. Most of the deliverables produced within the project are not confidential, to allow for the possibility to disseminate the project results among the entire scientific community interested in the activities carried out in SILER, and were published on the project website as soon as they were produced.

Particular attention was dedicated to the dissemination of information to young generations of scientists through a specific training program. A training course dedicated to the seismic issues in lead-cooled reactors was held in Verona, in May 2012 (www.siler.eu/Training%20course.htm). Moreover, some PhD theses have been defined on specific topics of the Project and worked in strong conjunction with the senior experts involved in the Project. A thematic workshop, open to the experience of correlated research areas, was held in June 2013, with invited lectures on specific topics strictly related with the major research issues on the seismic protection of LFR and ADS systems, alternated with presentations coming from a call for papers on several topics of general interest. Finally, an International Workshop was organized in Rome at the end of the project, where PhD students participating in the program presented the results of their activity.

6 CONCLUSIONS

The paper illustrates the main features of the SILER Project and the most important activities performed, with particular regard to the development, manufacturing and qualification of the isolators, and the most critical interface devices.

SILER demonstrated that the technology to isolate nuclear facilities already exists and that the main components like isolators (in particular High Damping Rubber Bearings and Lead Rubber Bearings) and flexible joints for pipelines (even the more critical ones) are reliable enough to guarantee the safety of the plant, even in the case of beyond design events.

SILER also confirmed the significant advantages given by seismic isolation, not only in terms of reduction of the seismic actions on the structure and most critical components, but also from the economical point of view, thanks to the possibility of standardizing the design of the reactor building, making it substantially independent of the seismicity of the construction site.

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