Seismic-Initiated events risk mitigation in LEad-cooled Reactors

**Executive Summary:**
The SILER Project aimed at studying the risks associated with seismic-initiated events in Generation IV Heavy Liquid Metal reactors, and developing adequate protection measures. Attention was focused on the evaluation of the effects of earthquakes on the structures and the most critical components, with particular regards to unexpected (beyond design) events, and on 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 lasted three years, from October 2011 to September 2014 and had an overall budget of 4.45 M€, 2.9 of which funded by EC. SILER activities were linked with the Sixth Framework Programme (FP6) projects ELSY ('European Lead-cooled System') and EUROTRANS ('EUROpean program for TRANSition prediction'), and the Seventh Framework Programme (FP7) projects LEADER ('Lead-cooled European Advanced Demonstration Reactor'), MYRRHA ('MYRRHA Accelerator eXperiment, research and development programme') and CDT ('Central Design Team (CDT) for a fast-spectrum transmutation experimental facility'). ELSY and MYRRHA have been selected as reference designs for SILER.

The SILER partners performed a deep examination of the risks and consequences associated with external dynamic loads on both Lead Fast Reactors (LFR) and Accelerated Driven Systems (ADS) components by analysing the global behaviour of the plants under seismic conditions. Specific layout solutions have been suggested and suitable seismic isolators have been designed, manufactured and tested, together with the related interface components like flexible joints for pipelines and cover joints to protect the seismic gap surrounding the isolated portion of the plant.

Reference was made to High Damping Rubber Bearings and Lead Rubber Bearings, which are among the most diffused and reliable seismic isolators. For the first time, very large full-scale isolators have been qualified and tested up to failure using real three-directional dynamic excitations, in order to define the safety margins in case of unexpected events. The experimental campaign demonstrated that, assuming a shear rubber strain of 100% at the design displacement, there are large safety factors (close to 3) against failure.

Moreover, suitable flexible joints have been developed for the pressurized hot steam pipeline going to the turbine building, which is the most critical one crossing the seismic gap between the isolated and non-isolated parts of the plant. A full-scale prototype has been manufactured and tested at the beyond design deformations under the service pressure (200 bars).

In addition, guidelines and recommendations have been issued, also based on economic analyses, with the aim of extending the use of the technology. Consideration was also devoted to transfer the knowledge developed in the project to Sodium Fast Reactors (SFRs) as well as to Generation III advanced systems, in line with the objective of the SNE-TP SRA to support present and future Light Water Reactors and their further development, for which safety issues are key aspects to be addressed. Note, in this respect, that the benefits of seismic isolation are already widely recognized for Generation III LWRs, along with the possibility of a significant standardization of structural and equipment design.

Finally, particular attention have been paid to the dissemination and exploitation of the results. A training course and two international workshops have been organized, and the results of the project published on the project website at www.siler.eu.

It is worth noting that the studies performed in SILER are continuing in the framework of the ESNII plus FP7 Project, making reference to the ASTRID and ALFRED reactors. SILER is expected to have a strong impact on the overall success of the LFRs and ADSs development programs, which strongly depend on developing, demonstrating and deploying advanced designs that exhibit, among other things, excellent safety characteristics.

Project Context and Objectives:
On September 21, 2007 the Sustainable Nuclear Energy Technology Platform (SNE-TP) was launched in Brussels, through which the European research nuclear fission community joined its efforts to issue a
The Strategic Research and Innovation Agenda (SRIA) for achieving sustainable nuclear fission energy. The main objective of the SRIA is to provide decision makers as well as the scientific community with clearly identified technological road-maps for the development of fission technologies, being the nuclear energy considered as one of Europe’s main low carbon energy technologies.

The SRIA of SNETP has been based, substantially, on the following ideas.

- Generation II and III Light Water Reactors (LWR) nuclear reactors contribute already very positively to the objectives in the EU’s energy policy. Existing reactors have an outstanding safety track record and they offer inexpensive base-load electricity; uranium supply is secure. In addition, nuclear power plants emit very low lifecycle greenhouse gases.

- Innovative Generation IV fast reactor systems with a closed fuel cycle will offer greatly improved sustainability. They will produce 50 to 100 times more electricity than current reactors from the same amount of uranium enabling natural resources to last thousands of years. In addition, with advanced fuel cycles and the partitioning and transmutation (i.e. recycling) of minor actinides and long-lived fission products, they will produce significantly less waste for disposal (in terms of volume, thermal load and radio-active inventory) thereby further reducing environmental impacts.

- Other Generation IV reactors operating at very high temperature will provide low carbon process heat for the mass production of hydrogen and other industrial processes, including desalination, thereby addressing major challenges for the future, i.e. replacing oil or extending its exploitation and supplying arid regions with drinking water.

Therefore, on the basis of the three abovementioned pillars, the SRIA highlights:

- R&D to support present and future LWRs and their further development with the aim to guarantee the present contribution to security of supply and CO2-free energy mix and enhance their competitiveness. Key issues are here certainly related to safety, in particular for the long term operation focusing on ageing of structures, systems and components.

- R&D challenges to further improve the current fuel cycles, with two objectives: improving the use of natural resources in LWRs through recycling strategies and minimising the final waste;

- R&D for the development of fast neutron systems (both Generation IV Fast Neutron Reactors (FNR) and Accelerator-Driven Systems (ADS)), along with the need for demonstration.

Looking at the area of the development of fast neutron systems, European stakeholders have chosen to concentrate their efforts along two directions.

- Sodium-cooled fast neutron reactor (SFR) is considered as a known and proven technology but for which innovations are necessary to fulfil the criteria of Generation IV reactors.

- In parallel, a coolant technology alternative to sodium, either lead or gas, will be selected between 2010 and 2012 to offer decision makers a choice of reactor systems and to limit technological risks. In this timeframe, the two systems will be compared in terms of potential, R&D needs and developmental timeline.

It is clear, therefore, that great efforts have to be put in identifying and addressing all the topics of major relevance for the demonstration of the abovementioned fast spectrum technologies in a short timeframe.

In this context, a topic of particular relevance is certainly the one of safety and mitigation of risks.

It is specified in the SRIA that “Nuclear reactor research in Europe has always had a strong focus on safety, and this will continue so as to ensure that European reactors continue to operate at the highest level of safety. Besides further research to increase knowledge in the basic nuclear sciences, research on human and organisational factors and plant-relevant issues such as Instrumentation and Control (I&C) and electrical equipment, or external hazards, will be addressed.” In general, in fact, it has to be noticed that to be sustainable energy production must avoid endangering the well-being of future generations, not only by
reducing the use of natural resources but also by minimising detrimental effects on public health and environment. This means that electricity production must achieve high levels of safety, both against internal and external damage events, and limit harmful emissions over the full lifecycle of the plant (cradle to grave). In particular, for Generation IV reactors maintaining and enhancing the safe and reliable operation is an essential priority in the development. Safety and reliability goals broadly consider safe and reliable operation, improved accident management and minimization of consequences, investment protection, and reduced need for off-site emergency response.

Generation IV reactors have to be highly secure and designed to withstand failure-driving events: their many protective features considerably reduce the impact of external or internal threats through the redundancy, diversity, and independence of the safety systems. This goal, strongly outlined in the Generation IV International Forum (GIF) roadmap, points out the need to increase public confidence in the security of nuclear energy facilities. Moreover, it has to be noticed that the diversity of the Generation IV systems and the need for a homogeneous strategy applicable for the design and the assessment of these systems justify an updated safety approach. The traditional approach to safety is one that has consisted largely of prescriptive requirements based largely on “engineering judgment”. The notion of the “design basis accident” as a bounding case underlies much of the historical safety basis for nuclear plants that began operation in the sixties and seventies. Advancements and analytical methods developed since then support an updated safety approach. Such an approach must include formal consideration of risk and safety issues throughout the design process, and must provide for prevention and mitigation relative to a broad spectrum of potential accident initiators and conditions.

In this light, a huge effort have been dedicated, ever, to continuously increase the level of safety of Nuclear Power Plants against internally initiated events, reducing the associated core damage frequencies. This has, therefore, forced the nuclear engineering community to concentrate a significant research effort also on the evaluation and mitigation of risks associated to external events such as natural hazards (earthquakes, hurricanes, tornadoes, flooding, tsunamis and so forth) as well as other external risks, such as terroristic attack (i.e. aircraft or missile impacts). Note that there have been recently a large number of external events that have severely challenged structures and operations of nuclear plants: flooding in France and Finland, several big earthquakes (one of them struck Kashiwazaki-Kariwa, the largest nuclear power plant of the world), the 2004 Indian Ocean tsunami (which affected the Tamil Nadu reactor in India) and the more recent catastrophe in Japan, which severely damaged the Fukushima plant.

Among all the possible external sources of damage, as demonstrated by a large number of Probabilistic Risk Assessment (PRA) studies performed worldwide, specific attention has to be paid to earthquakes, particularly challenging for their unique ability to initiate a fault event (also through indirect effects like landslides and tsunamis) and, at the same time, to cause failure of components needed to mitigate the accident itself; in addition, large uncertainties are associated to the earthquake occurrence and to the seismic performance evaluation of components and systems.

The seismic safety of nuclear installations is a subject that has received top-level attention by the scientific and regulatory community. For example, the IAEA Safety Standards have been developed since the 1970s and significantly improved in late 1990s. Today they are widely applied among the Member States. The seismic safety review services based on these Standards started in 1980s; at present more than 110 missions of interdisciplinary teams of experts were implemented in many countries during the site selection and evaluation phases, and for new and existing nuclear installations.

In this context there is a clear necessity to develop new methodologies, felt by the entire scientific and regulatory community, along with the need to identify new procedures and solutions in order to reduce the
overall core damage frequency in case of seismic events.

In fact it is believed that, through rigorous methodologies, it is possible to perform comprehensive risk analyses of nuclear plants to obtain accurate data and, subsequently, to study appropriate solutions for components, support, layout, siting, etc. The weak points in the design can be in this way detected, thus enabling the designers to modify the components-systems-structures and/or to identify possible protection systems in order to reduce the damage due to these critical contributors. The feedback could improve the layout of the plant (e.g. the distribution of structural elements within the containment and/or the buildings), or stimulate the study of technological solutions adopted for the components (e.g. supports or additional restraints), or affect the overall structural configuration (e.g. partial/total embedment, isolation, etc.).

This is particularly true for Generation IV reactor systems, and, among the six considered concepts, for the heavy liquid metal cooled systems, for which safety concerns in terms of response to severe seismic events are introduced by the use of thin walled components. Given the high temperatures of the coolant and the absence of pressure in the primary system, vessels and piping are relatively thin and elongated compared to Pressurized Water Reactors (PWR) components. Given that the masses are significant, such components are sensitive to inertial loads (i.e. seismic), then the buckling of the thinnest parts, the excessive stress in the supporting parts and the damage to the core itself are all phenomena that can occur and that is important to prevent.

For the Lead Fast Reactor (LFR) and Accelerator Driven Systems (ADS) design, important R&D technology gaps are identified in the SNE-TP SRA as well as in the Generation IV Roadmap, in system design at level of seismic protection, in particular with respect to selected components as, e.g. core internals support and refuelling machine design. The structural support of the reactor vessel, for example, containing dense Lead or Lead-Bismuth Eutectic (LBE) coolant, in fact, will require design development in seismic isolation approaches and sloshing suppression.

Major technological issues identified in the SRIA for the LFR development include, in fact, system design and component development including integrated core designs with appropriate safety features. For the system design and component development, one of the main concerns which could challenge the feasibility of the LFR is related to the large mass of lead, which claims for seismic isolation to prevent risks associated to earthquake phenomena. Particular concern is risen by sloshing of lead. As reported in the SRIA: “Lead sloshing (seismic induced or induced by a steam generator tube rupture) is a phenomenon whose importance is related to the high density of lead; even with efficient seismic isolation of the reactor building, the response of structures containing the large mass shall be evaluated.”

Main safety concerns related to immediate consequence of a seismic event in a heavy liquid metal reactor, therefore, are related to:

1. structural failures due to the dynamic loading,
2. core voiding by gas entrapped into primary coolant system,
3. functional failures of equipment due to coolant spill-out.

1) Dynamic loading on the elements of primary system in case of intensive seismic event can cause early core damage due to the following phenomena:

- Loss of coolant from the primary system. In most of contemporary pool-type designs loss of primary coolant is considered as very low probability because there is no piping below the coolant level and integrity of the vessel is considered as highly reliable. However, seismic events which can cause loss or leaks of primary coolant have to be considered seriously due to their consequences, even though the associated probability is very low.
Flow blockage in a fuel assembly. Most likely outcome of the coolant flow blockage in a fuel assembly is overheating and eventual disintegration of the fuel. In a worst case scenario degradation of one fuel assembly may lead to propagation of core damage to the neighboring assemblies. Thus quantification of dynamic loading which may lead to a damage of an assembly in a seismic event is important element of safety assessment.

Steam generator tube rupture (in LFR pool design). Steam generator tube is highly loaded thin element of the system. There is a number of threats which originates from steam generator tube rupture (SGTR) or leakage (SGTL). In a nutshell, a SGTR event generates a pressure shock wave and discharges steam/water into a molten lead environment, bringing the fluid (lead) into motion and creating a potentially energetic situation that imposes a dynamic loading on the surrounding structure. There is also gradual pressurization of the vessel after SGTR due to inflow of the steam which also requires design of appropriate protection measures for isolation of ruptured tube and safe depressurization of the vessel.

2) Core voiding is one of the major threats which can lead to rapid reactivity insertion and consequent core disruptive accident in Lead cooled Fast Reactors. In compact pool designs the flow path to the core inlet is, in fact, rather short. Gas bubbles can be dragged down by the coolant flow to the inlet of the core and cause core voiding and transient overpower (TOP) accident. Gas bubbles can originate from:
- sloshing and violent breakup of coolant free surface,
- steam leaking from a ruptured steam generator tube (in a LFR pool design).

3) There are also risks related to malfunction of different elements of the primary system due to spill-out of the coolant during the seismic excitation. These threats are design specific and can affect such systems as gas-dam thermal insulators.

Considering the abovementioned critical risks related to earthquake events, then, seismic isolation represents a highly attractive strategy. For example, for the Lead-cooled fast reactor concepts seismic isolation is explicitly regarded as a viability issue, as from the SNE-TP SRA.

Seismic isolation consists in the insertion, between the ground and the base of the structure, of suitable devices, called seismic isolators, which are very stiff in the vertical direction, to carry the dead load, and flexible in the horizontal ones, to allow lateral movements. In addition, seismic isolators usually dissipate a considerable amount of energy and provide a restoring force to limit the displacement during earthquake and the final off-set. Thus, the isolated structure assumes a quite low natural frequency (in a range where, generally, earthquakes have low input energy) and behaves like a rigid body above the isolation systems: accelerations and inertial forces, and then strains and stresses, are dramatically reduced and are almost the same at each level of the plant. This simplifies a lot the anti-seismic design of the structure and internal components and allows the standardization of the design, which become practically site-independent (for the horizontal component of the acceleration, at least). This is particularly important in the phase of development of new reactors, like those of Generation IV, when the construction site of the plant is still unknown and the economics is one of the GIF criteria.

More generally, seismic isolation is an effective tool for reducing or almost eliminating the devastating effects of earthquakes on people, equipment and structures. In particular, the use of seismic isolation can provide higher safety margins against failure of equipment and structural components in case of beyond design earthquakes, because the acceleration level at which the safe shutdown occurs can be significantly increased. This is extremely important not only from the safety point of view, but also from the economics,
in terms of operability of the plant.

It is worth noting that seismic isolation, being quite diffused in civil applications and already known especially in seismic countries like Japan and Italy, is positively perceived by the population and its application to nuclear plants certainly should have a good effect on the public opinion.

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 the very recent one, near the east coast of Honshu, Japan (March 11, 2011), which caused a 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 plant. It must be noted that, in isolated systems, large savings in terms of structural response are obtained at the price of significant relative displacements between the isolated building and the surrounding ground; these must be accommodated by the equipment (steam lines etc) and by the isolators themselves, which must be capable to absorb very large deformation maintaining their carrying capacity. In this respect, they are likely to become the “weakest link”, in terms of seismic fragility, of the entire structural/equipment system; these results in a clear advantage, since RD effort can be concentrated on the performance a single component. On the other hand, detailed studies are mandatory to assess the behaviour of the isolating devices up to failure conditions.

A research effort in the field of seismic protection of next generation reactors appears, therefore, to be worthwhile, paying special attention to the beyond-design-basis level, i.e. to the performance against extremely high seismic actions, as the ones which must be treated for a comprehensive evaluation of fragility and risk. In this light, the development of adequate isolation systems seems to be of great relevance in order to improve the level of seismic safety for next generation reactors. In particular, the use of isolation devices appears to be perfectly tailored within overall design frameworks employing passive mitigation strategies.

The latest violent earthquakes that struck Japanese nuclear power plants (Kashiwazaki-Kariwa in July 2007 and Fukushima in March 2011), renewed international focus on the structural strength of nuclear facilities. As already mentioned, safety and reliability are, in particular, essential priorities in the development and operation of sustainable nuclear energy systems: they have goals to achieve the highest levels of safety and reliability and to better protect workers, public health, and the environment through further improvements. This also reducing the likelihood and degree of damage due to unexpected, strong external accidents with very low probability of occurrence, like, indeed, very strong beyond-design earthquakes. The development of adequate and numerous protective features for considerably reducing the impact of external or internal threats through the use of redundancy and separation of safety systems, then, is an issue that has necessarily to be considered in developing Generation IV nuclear systems and transmutation devices. In this view, the development of appropriate isolation strategies for all the safety-related part of the reactor is a fundamental issue.

In this contest, the SILER Project has been developed and then accepted and funded by EURATOM in 2011, within the 7th Framework Programme. In SILER the attention was focused on the evaluation of the
effects of earthquakes (with particular regards to beyond design seismic events and tsunamis) and to the identification of mitigation strategies, acting both on structures/components design as well as on the development of isolation devices, which can also have positive effects on economics, leading to an high level of plant design standardization. Specific effort was devoted to the development of guidelines and recommendations for addressing the seismic issue in next generation reactor systems. In addition, consideration was devoted to transfer the knowledge developed in the project to SFR systems as well as to Generation III advanced systems, in line with the objective of the SNE-TP SRIA to support present and future Light Water Reactors and their further development, for which safety issues are key aspects to be addressed. Note, in this respect, that the benefits of seismic isolation in terms of response to design seismic actions are already widely recognized for Generation III LWRs, along with the possibility of a significant standardization of structural and equipment design.

Specific objectives of SILER were:
- the identification of the main features of lead-cooled reactor concepts (LFR and ADS) relevant for evaluation of the risks associated with external damaging;
- the evaluation of the selected system behaviour in case of severe seismic accident; in particular, a key objective is the evaluation of the seismic related movement leading to failure of the primary system; specific consideration is paid to the study of sloshing;
- the identification of mitigation strategies through the design of adequate reactor components (i.e. vessel supports, core supports, spent fuel storage pools, steam generator tube supports, joints, foundation slab, etc.) and the development of specific devices (i.e. isolation devices) for structural damage reduction as well as the development of suitable layout design options to avoid the release of radioactivity (i.e. from the fuel storage pools);
- the evaluation of the economic benefits related to the introduction in the reactor design of measures for reducing the reactor damage due to external events, with the consequent increased standardization in the design;
- the transfer of the knowledge gained on the advanced measures for increased safety from external risk mitigation to Gen III LWR technologies.

Project Results:
The SILER project intended to study the risk associated to seismic events in Heavy Liquid Metal reactors (LFR and ADS) and developing adequate protection measures.
In order to meet the project goal, specific actions have been foreseen:
1. the identification of the main features of LFR and ADS concepts relevant for safety analyses as well as the identification of the input data needed for assessing the external damaging events effects, to permit the evaluation of the selected reactor systems behaviour in case of seismic accident.
Specific activities were:
- the realization of adequate structural models of the reactors and their components;
- the realization of adequate models of seismic isolators;
2. the assessment of the system behaviour under seismic excitation. Running numerical analyses has permitted to evaluate the seismic behaviour of the abovementioned systems with particular attention to the following aspects: (a) the simulation of complex dynamic phenomena, such as fluid-structure interaction, in which local equipment response could undergo significant coupling with the overall motion of the isolated building, thus jeopardizing the efficiency of the isolation system itself; the study of sloshing will play a key role in such activity; (b) the evaluation of the risk associated with the seismic motion for the isolated
systems, with particular reference to the seismic fragility evaluation, namely the probability of failure of a component (or structural element) conditioned to the severity of the ground motion;

3. the identification of mitigation strategies. Here particular attention was devoted to seismic isolators development and manufacturing. Efforts have been dedicated to the characterization of the mechanical behaviour of isolators up to failure through the performance of experimental testing and numerical analyses;

4. the design of adequate reactor components, specific devices and layout solutions for damage reduction. The attention was focused on particularly critical components (i.e. the protonbeam-line and the target in ADS type reactor) as well as on all the structures and components that it is necessary to introduce on the basis of the isolation of the reactor system (i.e. foundation slab, containment wall, joints, etc.). Particular attention was also paid to investigate design solutions which can mitigate the risk of earthquake induced damage, as, for example, for reducing the risk of radiation emission from the damage of spent fuel storage pools. Moreover, the choice of a suitable “end-condition” for isolators was addressed; this condition could be put on relative displacement, by introducing shock absorbers to prevent the isolator failure (or vertical instability) and rigid hammering on surrounding soil retaining wall (embedment of future NPPs is assumed for other security considerations). The dynamic response and design implications of such strategies were addressed;

5. the development of recommendations for mitigating the risks due to seismic events in heavy liquid metal pool type reactors. Attention has been paid to the evaluation of the economics derived from the mitigation of the failure risk related to earthquakes as well as from the high level of standardization derived from the plant seismic isolation. Specific actions were also the development of guidelines for the design, manufacturing, qualification, installation and maintenance of seismic isolators as well as studies for the knowledge transfer on external risk mitigation to Gen III LWR technologies.

6. 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. Attention has been paid paid to training of PhD students and researchers active inside the consortium.

On the basis of the above described six main actions, the project is structured into six technical work packages, each one corresponding to one of the abovementioned specific goal, plus two dedicated work packages aimed at managing the consortium activities and the scientific coordination, respectively, as follows:

WP2: System modelling
WP3: Risk analysis for critical components
WP4: Development and characterization of isolation devices
WP5: Additional components design
WP6: Recommendations for standardization
WP7: Dissemination of information

plus:
WP1: Consortium management
WP8: Scientific coordination

WP2 aim has been the numerical modelling of selected reactor systems (LFR, ADS) for evaluating their
behaviour in case of seismic accident and individuating possible countermeasures for limiting reactor damage. It has the specific objective of collecting all the necessary information for the modelling of the two reactor concepts and of their key components, as well as of the isolators.

Therefore WP2 has been the first step for the research carried out in other Work Packages, and produced four reports containing the input data for other WPs.

In detail, the first report contained the description of the selected systems (D2.1). It included all the needed features and contained the generation of specific Time Histories according to the relevant spectra, as well as the use of previous projects as base for the current SILER project.

The second report contained the description of the design of seismic isolators (D2.2). Simplified models of the isolators were developed to be used in the reactor modelling. Very accurate models including non-linear behaviour were prepared, and some of them were updated to match with the empirical results obtained from the tests carried out inside the project scope.

D 2.3 contained the description of the model of the reactor systems. This report consisted of a mere description, having no special feature.

Finally, the fourth report (D2.4) contained the description of the dynamic behaviour of systems. The results of the analyses carried out are summarized in this deliverable, with the aim of obtaining relevant conclusions. Taking into account that the main analysis consisted of running the model for many different cases of isolation, soil and earthquake, the results showed a very good coherence with the system analysed. Isolation devices reduced the fundamental frequency of the structure, as expected, and strongly reduced the acceleration. Vertical motion however did not experience special reductions in such variables, logically, and showed a great coupling with the soil parameters.

The aim of WP3 was to evaluate the risk of damage of components and structures due to seismic excitation. Attention was devoted to the sloshing phenomena, considered as key issue in HLM systems. Detailed models of the reactor vessel have been generated (task 3.1) and the main internal components for studying sloshing effects, moving for the response spectra at component locations produced in WP2. These models behaviour have been evaluated with FLUENT approach.

Fluid and structural analysis have been carried out in order to obtain the fluid and solid solution fields. For the structural analysis ANSYS code has been used.

In order to evaluate the fluid structure interaction, two models of the ELSY/LFR reactor have been developed. In the first one, the reactor has been modelled as a rigid body, and in the second one, the main components (heat exchangers and steam generators) have been modelled as rigid bodies, but the external and the cylindrical inner vessel have not been modelled like that. Those models have been processed with ABAQUS.

Four seismic load scenarios of the different seismic inputs for all cases described above have been run. The objective was to obtain information on the sloshing of the free surface and on the fluid-structure interaction, with both approaches.

From the examination of the studies described above, responses from the two models are compared to conclude with the significant loads on the vessel and vessel lid and on the internal components.

The following results have been obtained in the study of sloshing effects:

In order to ensure the stability of the calculation is necessary to develop models with a high number of elements. The instability also depends on the load level. It means that it is required to have a high capacity of data storage and, to avoid long calculation times, work with high capacity computers.
The maximum pressure in the inner and outer vessel reaches values several times higher than the pressure associated with the hydrostatic pressure. This implies high stresses on the internal components of the vessel.

During seismic response, high specific pressures in small areas and for short time intervals are generated. These pressure pulses are responsible for the identified peaks in the pressure histograms.

In the process of dynamic response calculations it has been shown that the liquid lead was in contact with the upper cover, thus generating significant areas with big loads on the vessel lid.

The interaction between the coolant and the internal components generates significant loads on the upper cap of the vessel. These loads and their transmission mechanisms should be evaluated in detail.

The comparison of the calculations with rigid vessel and with flexible vessel, shows that there is an effect of fluid structure interaction that must be taken into account.

The high pressures on the vessel show that local stresses can be very high. This generates a major impact on the design of the reactor vessel, which may require, well a geometry change with a thickness modifications or a material change in order to modify mechanical capabilities.

The liquid lead sloshing has also been investigated using CFD approach in which the fluid flow is simulated according to Reynolds-Averaged Navier-Stokes (RANS) formulation coupled with VOF model to track the liquid metal-gas interface. The domain of interest includes the cold free surface region between two steam generators in the ELSY primary system. To choose an optimal mesh for inexpensive simulations while providing sufficiently accurate solution, a grid sensitivity study on a dam break case is performed.

A domain of seismic loading parameters that lead to adverse effects in terms of hydrodynamic forces and gas entrapment characteristics have been identified. In particular, a map of sloshing regimes in the seismic excitation space have been generated. This space is defined by the frequency and amplitude of the excitation function. The ranges for frequency and acceleration used in this analysis have been obtained from earlier studies performed in the field of reactor seismicity analysis covering the reactor prototypic conditions. For a given geometry of the tank containing the fluid, parameters characterizing the dynamics of free surface motion determined the regime of sloshing.

The results of two-dimensional CFD analysis performed suggested that near-natural frequency and high amplitude excitation leads to violent sloshing with highest waves, velocities and strongest pressure peaks at the walls. It was demonstrated that excitations with frequency of 0.4-0.5 Hz lead to sloshing already at fairly low (0.1 g) input acceleration amplitudes. Predicted pressure peaks from 5-10 bars at the vertical walls and the reactor roof suggest that coolant sloshing should be considered in the design of an LFR as a possible threat to the vessel structural integrity.

Three-dimensional analysis confirmed the presence of high pressure values at the reactor roof. Peaks between 2 and 22 bars were monitored in simulations with discrete input. Simulations with artificially synthesised, time-dependent seismic input spectra show that in most cases the pressure peaks stay within 1-2 bars. This can be explained by the mutual interaction between excitations in different directions (dampening). However, to quantify this effect, dedicated simulations are needed.

Regarding gas entrapment, the 2D and 3D discrete seismic input simulations showed more violent sloshing than simulations with multi-dimensional synthetic time-histories for seismicity.

The complex dynamic phenomena related to the accelerator/reactor coupling under severe seismic condition have been studied (task 3.2). Specifically, the following aspects have been analyzed:
Relative displacement between Proton Beam and hexagonal wrapper;
Stress and failure of the coupling proton beam/hexagonal wrapper.
The analysis has been developed through the following steps:
PHASE 1: Definition of seismic input loads
Seismic input choice among the different seismic configurations of Reactor building studied in WP2
Definition of cases to analyse
PHASE 2: Global FEM of ADS reactor and its internal
Linear dynamic analysis for specific case of soil, seismic level and foundation layout, defined in WP2 activities;
For each case, results in term of displacements and accelerations have been evaluated in correspondence of some interface points (IP) with Proton Beam, core and hexagonal wrapper.
PHASE 3: Local FEM of Proton Beam assembly
Linear dynamic analysis considering as input load IP result of the global model
Design the location of spacers between hexagonal wrapper and Proton Beam arising from the analysis results with different spacer configurations up to reach the design value of relative displacement equal to 2 mm among the two components.
Stress analysis of the main internal components

The following results have been obtained in the study of the ADS:
Five intrim guides between Proton Beam Tube and Hexagonal Wrapper are to be designed to achieve the objective of having a maximum relative displacement of less than 2 mm
Stresses on the structure were calculated for all selected load cases (non-isolated DBE and BDBE, HDRB seismic isolation DBE and BDBE corresponding to CASES 1, 2, 6, and 7, respectively). Both for Proton Beam Tube and Hexagonal Wrapper stresses result to be within the yield stress in all the zones of the components for CASE 1, CASE 6 and CASE 7. With SI application the stresses at the both Hexagonal Wrapper and Beam Tube are reduced by about a half.
For CASE 2 instead, there is a critical stress scenario in the upper zone of the structure, in correspondence of the connection of the components to the Steel Cover.
The SI solutions for ADS MYRRHA are evaluated in 3 different cases such as SI of whole Reactor Building, SI of Reactor Vessel only, and SI of Reactor pedestal only, and the Seismic Isolation of the whole Reactor Building is recommended.

Activities aimed at the development and testing of a numerical procedure for estimating the seismic fragility for equipment and structural components of base isolated Nuclear Power Plants have been performed (task 3.3). The procedure has been applied to the preliminary design of the NPP reactor building of ELSY; the building is equipped with a base isolation system composed by High Damping Rubber Bearing elements showing a markedly non-linear mechanical behaviour. When seismic isolation is introduced, resulting in a dramatic reduction of horizontal accelerations inside the building, attention is focused on the behaviour of the isolation devices, while the dynamic behaviour of the building can be captured by means of simple mechanical models, based on the introduction of a limited numbers of rigid bodies representing the building and its foundation (in the case here studied the entire system has 15 degrees of freedom).
Therefore, the fragility analysis has been performed assuming that the isolators become the critical elements in terms of seismic risk: the relative displacement across the isolator has been here assumed as
the response parameter governing its limit state. Within this context, a suitable force-displacement model is necessary to closely represent the isolator inelastic response to horizontal loading: here, a literature detailed model of the device (Abe, Fujino, 2004) has been adopted and coded in ABAQUS SW. Six Random Variables have been introduced in the fragility analysis: shear modulus and damping factor of the ground, isolator stiffness, damping and deformation capacity, accidental global eccentricity. For each realization of a set of the RVs a random vibration problem has been solved by simulation, to get the mean value and standard deviation of the extreme relative displacement of the most stressed isolator. The Response Surface Methodology has been adopted to model the influence of the random variables on the response of the structure. Response Surfaces are then refined adding the design points computed by the First Order Reliability Method (FORM). The computation has been repeated for 16 pga values (from 0.3g to 1.8g) each including 43 experimental points (i.e. different numerical combinations of the RV’s). Each experimental point includes a set of 20 artificial time-histories compatible with the spectrum required by Eurocode 8 Type 1 Ground C, each described by the three components of motion. The fragility curve has been obtained, showing that in order to get a probability of failure for the most stressed isolator of about 50% a pga equal to 1.3g is required. If a pga equal to 0.9g is considered, the probability of failure drops down to 10%. Significant considerations have been also developed in relation to the contact between the isolated structure and the foundation, the axial behaviour of the isolators, the evolution of relative displacements and axial forces in the isolators.

A study has made to comprehensively define the scenarios starting from a plant damage state governed by the initiating seismic event ending with different failure modes. Furthermore, various types of uncertainties associated with each steps in a scenario are identified and in some cases, resolved. The aim was to provide a general framework to estimate the risk of seismic sloshing induced hazards in a pool-type LFR. An overview of risks related to seismic sloshing have been provided. Seismicity-related phenomena in a lead-cooled fast reactor has been described in terms of safety concerns and issues contributing to the seismic risk due to sloshing. An IDPSA framework for risk assessment with qualitative definition of safety goals to assess the risk have been proposed. Special attention is put on the contribution of uncertainties to the overall risk assessment. The sloshing risk analysis approach is described stepwise and finally exemplified on a case of ELSY LFR hypothetically built in Romania – a location chosen for an LFR demonstrator ALFRED.

Based on a standard degradation law, lifecycle assessment of the systems and their components has been defined. It comprises a three pillar model consisting of visual inspection results, analysis of standard requirements and the input received from non-destructive testing (NDT). Within the SILER project an adaptation and extension to the needs of the nuclear industry is performed. Specifically, a basic model for lifecycle assessment of the systems and their components is made available which enables the production of a specific tool suited for the requirements defined by the SILER project. Also, a proposal is made how this risk assessment could be structured. The IRIS risk paradigm has been implied in various industries successfully and all the basic work to establish an operable risk framework is completed. Furthermore, the various existing standards and regulations are mapped which might play a role in this assessment procedure. It shall be mentioned that these applications have a high attention in the energy industry and are widely accepted.
WP4 was aimed at the development, design and manufacturing of the seismic isolators (based on the outputs of task 2.3) and the execution of the experimental tests needed for their characterization. Three rubber compounds, one high damping and two low damping, were developed and tested (Task 4.1). The low damping compounds are aimed at use in Lead Rubber Bearings (LRB), in which the energy dissipation capacity is given by yielding of one or more lead cores. The high damping compound is aimed at use in High Damping Rubber Bearings (HDRB). All the compounds were developed in order to provide high failure limits, to guarantee high safety factors to the isolators.

The main results obtained are:

The high damping rubber compound developed has a shear modulus $G=1.4$ MPa and an equivalent viscous damping higher than 10%, measured at shear strain 100% and frequency 0.5 Hz.

One low damping compound has a dynamic shear modulus of about 1 MPa and equivalent viscous damping of about 6 %, measured at shear strain 100% and frequency 0.5 Hz. The second compound has a dynamic shear modulus of about 1.4 MPa and equivalent viscous damping of about 7 %, measured at shear strain 100% and frequency 0.5 Hz.

After many preliminary tests on small rubber specimens, the pre-selected compounds were used for isolator prototypes of two different sizes: diameter 200 mm and diameter 500 mm. These prototypes were subjected to many tests.

The prototypes with diameter 200 mm were used both for compression-shear tests, and for compression/tension tests. The compression-shear tests were used both for the characterization of the compounds, in terms of shear modulus and equivalent viscous damping, and for tests up to failure. The tests in compression and tension were aimed at quantifying the differences between tension and compression behaviour, and thus at providing data for modelling. Tension tests have been carried out up to failure, to measure the safety factor in tension. Tension tests showed an higher non-linearity in tension than in compression.

Tension tests showed that the maximum tension stiffness is much lower than that in compression, about $1/7 \div 1/8$.

Failure in shear happened at a shear strain of about 500%, a very high value.

The prototypes with diameter 500 mm and a total rubber height of 126 mm were used for compression-shear tests up to a shear strain of 200 % (dynamic tests), and then up to failure. The main aim of these tests was to check the mechanical properties of the rubber compound in a full scale isolator. In effect, the diameter 500 mm prototype can be considered as a reduced scale prototype of isolators designed for NPP, but can be considered as a full scale isolator for other applications, e.g. buildings.

The results of compression-shear tests on diameter 500 mm prototypes confirm the values of shear modulus and equivalent viscous damping obtained on smaller prototypes.

HDRB have been designed for both ELSY and MYRRHA reactors (task 4.2) using the high damping rubber compound developed within task 4.1. The HDRB has been designed according to the European Standard EN15129:2009 “Anti-seismic devices”, with additional prescriptions established within SILER project, for example to design the isolators with shear strain at design displacement at Design Basis Earthquake not higher than 100 %, in order to guarantee an high safety factor against failure even at Beyond Design Earthquake.

The isolator selected to be manufactured as full scale prototype has been the isolator designed for ELSY reactor. Said isolator – identified by the mark SI-H 1350/256 – has a diameter of 1350 mm and a total rubber height of 256 mm. These very large dimensions have been a challenge for manufacturing.
A specific testing programme has been prepared, with cooperation amongst the partners involved in the WP4 and the members of the External Advisory Committee.

In particular, one of the manufactured prototypes was subjected to a complete testing campaign, comprising not only the Type Tests according to the European Standard EN 15129, but bidirectional and tri-directional time-history tests as well. Bidirectional tests are tests in which a constant vertical load is applied, and contemporarily the horizontal displacement is applied along two orthogonal axes instead of one only (as in most of the standard type tests). In particular, the horizontal displacement was applied following the displacement time-histories obtained as an output of the non-linear analyses on the structure, on some of the isolators. Similarly, in tri-directional tests, horizontal displacement time histories were applied along two orthogonal axes, and the vertical load time history was applied as well: i.e. instead of keeping constant the vertical load as usually in type tests according to the Standards for civil applications, the variation of the vertical load during the earthquake was considered, using the output of the non-linear analyses on the structure. As far as we know, this is the first time that these bidirectional and tri-directional time-history tests have been carried out on elastomeric isolators of such dimensions, in particular on isolators specifically designed for nuclear power plants.

In total, 5 bidirectional or tri-directional time history tests were carried out on the same isolator. All the bidirectional and tri-directional tests were fully satisfactory; the isolator behaviour was as expected in both horizontal directions.

The Type Tests according to the European Standard EN 15129 were also carried out, up to failure, corresponding to a Beyond Design Earthquake larger than 2.5 times the Design Basis Earthquake. One of the most important result of said testing campaign is that the isolator, even after failure, can support the vertical load and can sustain aftershocks as well, offering some energy dissipation and displacement control. In effects, after the failure test, a quasi-static compression-shear test at 100 % shear strain was carried out, in order to check the behaviour of the isolator even after failure. The results of this tests show that the isolator has a much lower horizontal stiffness than before failure, but it is still able to keep the vertical load and offer a certain horizontal stiffness and energy dissipation.

The main results are summarised as follows:

HDRB were designed for both ELSY and MYRRHA reactors.

Full scale HDRB prototypes of diameters 1350 mm and a total rubber height of 256 mm, designed for the ELSY reactor, were manufactured and subjected to many tests.

In particular, one prototype was subjected to a complete testing campaign, including bidirectional and tri-directional time history tests. This kind of tests were never performed before on isolators of such sizes designed for Nuclear Power Plants. All the bidirectional and tri-directional tests were satisfactory; the isolator behaviour was as expected in both horizontal directions.

Complete type tests according to the European Standard EN 15129 were carried out as well on one prototype.

The failure was reached at a displacement corresponding to a Beyond Design Earthquake larger than 2.5 times the Design Basis Earthquake, confirming a very high safety factor.

Repetition of the compression-shear test at 100 % shear strain amplitude on the failed isolator show that the isolator, even after failure, can support the vertical load and can sustain aftershocks as well, offering some energy dissipation and displacement control.

LRB have been designed (task 4.3) for both ELSY and MYRRHA reactors using the low damping rubber
compound with shear modulus G=1.4 MPa developed within task 4.1. The LRB have been designed according to the European Standard EN15129:2009 “Anti-seismic devices”, with additional prescriptions established within SILER project, for example to design the isolators with shear strain at design displacement at Design Basis Earthquake not higher than 100 %, in order to guarantee an high safety factor against failure even at Beyond Design Earthquake.

The isolator selected to be manufactured as full scale prototype has been one of the two types of isolators designed for MYRRHA reactor, in particular the stiffest. This isolator – identified by the mark LRB 1250x1250/192-200q – is a square isolator, with a side of 1250 mm, and 4 lead cores, each with diameter 200 mm. Total rubber thickness is 192 mm. These very large dimensions have been a big challenge for manufacturing: special care was necessary both in the design and construction of the mould and in vulcanization of the prototypes.

Two full-scale prototypes of LRB 1250x1250/192-200q have been manufactured and tested up to the limits of the biggest testing rig in terms of horizontal force (2000 kN). This limit was enough to measure the bilinear behaviour of LRBs and check it in comparison with the theoretical bilinear curve. Such comparison shows that the experimental behaviour is fully in agreement with the expected theoretical behaviour.

The main results are summarised as follows:

LRB were designed for both ELSY and MYRRHA reactors.

Full scale LRB square prototypes, designed for MYRRHA reactor, were manufactured and subjected to tests. The prototypes are the stiffest isolator type amongst the two types designed for seismic isolation of the MYRRHA reactor; consequently, their dimensions are very large.

The full scale isolator prototype is a square isolator, with a side of 1250 mm, and 4 lead cores, each with diameter 200 mm. Total rubber thickness is 192 mm. The compound used in the manufacturing of the prototypes is one of the new low damping rubber compounds developed within the framework of Task 4.1. It is a compound based on natural rubber, with effective dynamic shear modulus G=1.4 MPa at shear strain 100% and frequency 0.5 Hz.

Two full-scale prototypes of LRB have been manufactured and tested up to the limits of the testing rig in terms of horizontal force (2000 kN). This limit was enough to measure the bilinear behaviour of LRBs and check it in comparison with the theoretical bilinear curve. The comparison between the experimental hysteretic cycles and the theoretical bilinear curve show an optimum agreement.

Aim of the WP5 was the design and manufacturing of innovative interface components connecting the isolated and non-isolated parts of the plant, or components requiring a specific design in case of isolation of the system:

- to produce seismic isolation design solutions for the ADS interface components
- to design, manufacture and seismic test for the flexible pipe joints
- to design and analyse the foundation and isolated concrete slabs, respectively below and above the isolation system, which are probably the more sensible and expensive structure to be built.
- to design, fabricate scaled prototype and test for the joint cover of the seismic gap
- to design and analyse the fender system as fail safe system to prevent and reduce the hammering load to be imposed on the reactor building against the beyond design basis case
- to investigate to mitigate the risk of earthquake induced tsunami and/or flooding and earthquake for the
LFR reactor systems and recommend the design solutions to mitigate the risk

Three different seismic isolation (SI) application for the ADS reactor system have been set up to clarify the workscope among WP2, WP3.1 and WP5.1 and design procedures for the different SI applications for the ADS have been established (Task 5.1):
1) whole reactor building (RB) seismic isolation,
2) reactor vessel (RV) seismic isolation only with fixed base reactor building, and
3) reactor pedestal seismic isolation only with fixed base reactor building.

In the study 1) schematic design concepts of the different seismic isolation solutions for the ADS are proposed, 2) corresponding design of the interface components to the different seismic isolation solutions are suggested, 3) seismic input motions due to different positions of seismic isolations are also setup using the results provided by WP2, then 4) the corresponding seismic responses such as accelerations and relative displacements are obtained and compared using simplified analyses for the different seismic isolation solutions for DBE and BDBE conditions.

In general the application of the seismic isolation for the different SI solutions can reduce more seismic loads than non-isolated fixed base case, consequently it would be only possible for the SI solutions to meet the seismic design requirements for the safety related structures, systems and components subjected to DBE and BDBE.

The ADS interface components affected from three different seismic isolation solutions under severe seismic conditions as DBE and BDBE have been identified for the D5.3 for Task 5.1 of WP5.

In the case of SI of reactor vessel only, the support structure of the proton beam line inside of the containment boundary is designed with two options; gantry type or jib crane type. To avoid complex interface with the remote handling machines and to provide more space above the reactor cover, the Jib crane support type of the proton beam line is recommended.

However the large seismic gap around the reactor vessel would not meet the safety requirement of emergency heat removal if the failure of the reactor vessel results in the leakage of the LBE coolant which can’t cover the reactor core due to large seismic gap consequently no natural circulation of the coolant for the reactor cooling. And the RV SI solution makes connecting design complicated for the interface components above the reactor cover. In addition the irradiation effect on the isolators near the reactor would be an issue.

In case of SI of the reactor pedestal only, design of the safety related interface components to accommodate large displacement around the containment boundary and containment safety requirement containing all radioactive material inside the containment boundary are too complicated to meet seismic safety of the safety related components.

The design of the proton beam tube inside the reactor vessel would be the same for the different SI solutions proposed since the interface points between non-isolated and isolated structures are not occurred inside the reactor. The structural integrity of target (Hexagonal Wrapper) and beam tube under DBE and BDBE in the reactor could be met with the design implementation of 5 guide thimbles in between the hexagonal wrapper and the beam tube.

Thus the Seismic Isolation of the whole Reactor Building is recommended based on the study since there is no safety issue related to interface components when the whole reactor building is isolated.

Expansion joints/expansion joint systems have been identified (task 5.2) that are, based on preliminary
analysis, capable to compensate for the required seismic displacements for both ADS and LFR reactors. Further a model has been developed to simulate the behaviour of the expansion joint system in the ADS beam line under seismic events computed in WP2. And the simulation confirmed the capability of the system to compensate for the computed seismic excitation.

Regarding the LFR reactor, it has been completed the design of expansion joints that are capable to meet the design requirements for the Main Steam (MS) and Feed Water (FW) piping systems and successfully manufactured a full scale prototype expansion joint (hydraulic forming of the bellows) for testing at EC-JCR’s test facilities. And a hydrostatic pressure test of the complete expansion joint has confirmed the integrity of the joint.

Computed properties of the MS and FW expansion joints have been communicated to EC-JCR for consideration for the test set-up and data recording.

A possible testing solution has been elaborated, which ensures representative loading conditions in the expansion joints: the rotation and shear forces histories induced by the seismic loading as well as the normal force due to the internal pressure would be applied quasi-statically on a full-scale bi-dimensional joint linked to two pipe segments.

A risk based assessment model has been developed for describing the performance of a system under variable conditions, and undertook several studies to make the testing of the piping and pipe joints feasible at JRC. This also comprises a special solution for the pressurized specimen to connect to the testing equipment.

It shall subsequently be applied at the large scale tests planned by EC-JRC.

It consists of the 3 major components of risks which are: hazard, vulnerability and consequences. They are broken down to factored elements which are connected to individual uncertainties of the aleatory or epistemic type. The final product enables sensitivity studies by showing how uncertainties can be reduced using permanent online monitoring systems.

Concentration has been put on the vulnerability models which compute the useful fragilities and on the consequence model (or performance model) which enables the desired variation.

The use of expansion joint in the nuclear industry has been investigated, which is not common and presents difficulties in design, control and manufacturing. Nevertheless certain difficult points can be removed with R&D and codification programs. Recommendations were made concerning specific points to improve with the goal of implementing the new design into the code for future use.

A design of the joint cover of seismic gap has been performed (Task 5.3) to accommodate the horizontal displacements outlined in WP2, equal to ± 0.3 m (DBE) and ± 0.9 m (BDBE). In addition to the displacement requirement, the joint had to provide resistance to fire, flooding and the mechanical loads during operational and disaster conditions. A design concept has been provided, which uses a telescopic setup of three metal sheets to provide the desired sliding capability. Within the range of the DBE, the sliding can occur unhindered. A mechanical fuse (shear bolts) prevents catastrophic failure in the case of a BDBE, so that the covering of the reactor tunnel is still maintained.

Fire resistant rubber seals between the sheets make the construction watertight. The seals are kept in permanent contact with the sheets via elastomeric bearings which set a constant distance between the sheets. Currently a special rubber compound matching with class B1 of DIN 4102-1 (hard to burn) has
been selected. After the concept was refined, it was validated by means of finite element simulation. The load case which was considered as a worst case scenario is a flood level of three meters in the BDBE-extension configuration. It could be shown that the stresses are not critical and the resulting displacements do not cause failure of the seals. Finally, a prototype (2.5 x 3.45 m) was built with the aim of testing the functionality of the device in real seismic conditions. The specimens has been tested at the UTTMAT-QUAL laboratory of the Casaccia Research Centre, by applying three seismic tests and a series of combined XY sine tests at the maximum displacement performance of the shaking table (corresponding to the design displacement of the device). The time histories of the seismic tests had different spectral acceleration content, representative of soft and medium soil type, according to the USA Regulatory Guide 1.60: ‘Design Response Spectra for a Seismic Design of Nuclear Power Plants’ and the EUROCODE 8, type 1, ground type E. In addition, some tests were conducted by moving the shaking table in x and y directions up to its displacement limits (manual control tests). Sine and sine-sweep tests were also carried out. Finally, the test campaign performed on the shaking table demonstrated the full reliability of the device.

It have been addressed the structural issues when adopting the base isolation concept in nuclear plants (Task 5.4) focusing on the conceptual design of the LFR and ADS base isolated plants foundations by identifying requirements, specifying performance needs and providing criteria for actual design of base isolated nuclear power plants. Activities focused on the ADS MYRRHA nuclear island, characterized by bigger dimensions and higher mass than LFR, thus resulting in a more severe set of forces to be considered in the conceptual design using existing international standards dealing with the design of base isolated structures, and, in particular, to the set of the Eurocodes. Seismic input used has been defined by two types of spectra, depending on the type of soil considered. Analyses have been carried out based on these spectra. For hard soils, the seismic input is defined by the spectra given in RG 1.60 extended to Central and Eastern USA, while for soft soils the elastic spectrum is defined according to EN 1998-1 for spectrum type 1, soil type E. For each type of soil, and therefore for each type of spectrum, terms of artificial spectrum-compatible time-histories have been developed by partner EA. In addition, further synthetic accelerograms have been defined by Numeria for DBE conditions based on EC-8 spectrum, by paying particular attention to the high periods energy content. Based on the theory of base isolation, on the critical review of International Standards, as well as on the results obtained from the activities carried out on MYRRHA, general design provisions have been proposed for a base isolated nuclear plant. Criteria for the design, of either the superstructure and substructure, in DBE and BDBE conditions have been assessed. In particular, aspects related to elastic behaviour requirements, control of deformations, specifications/limitations on ductility demand on the superstructure, deformability limits for piled foundations have been investigated by linear and nonlinear analyses. The definition of a procedure for the installation and replacement of the isolators has also been addressed. The final results of task’s activities provided input for WP6 “Recommendations for standardization” thus contributing to a draft of an European Standard or Guidelines on base isolated nuclear plants, at present still missing.
Parametric analysis have been performed (task 5.5) to evaluate the displacement in case of events with a PGA beyond 3 times the DBE using simplified model of the structure, linear model of the isolators. Even if the probability of an event exceeding the Beyond Design (BD) condition is extremely low, a fail-safe system must be installed because, also in case of beyond design earthquakes, the isolators shall never lose the capability of supporting the vertical load. In case of strong torsional effects, it can also limit the excessive local displacement.

Taking into account these aspects, it could be a good choice to use, as fail safe system, the surrounding retaining wall that is separated by the base of the building with a gap (wall-gap) allowing the free movements of the base during ground shaking. Thus, making the gap large as the maximum isolators shear strain, the surrounding wall can be used like a “hard-stop”. In this case, during a beyond design earthquake, several impacts that can damage the reactor could occur. In order to avoid this effect, the fail safe system must reduce the forces generated during the collisions between the buildings and the surrounding wall.

In order to reduce the amplitude of the impact forces, the usage of a bumper system was investigated. Among the different type of bumpers it was chosen the marine fender device that is commonly used to absorb the extra forces due to impact between the vessel and the docking structure of the pier. The marine fender is a good trade-off between the performance in terms of energy absorbing characteristic and low cost of installation.

The design of the fail safe system based on the fender device was performed taking into account their reaction force, energy absorption, and deflection curves.

The utilization of a fail-safe system is recommended to guarantee the safety of the nuclear plants, even if it is activated only during an extremely rare event with a PGA 3 or more times the DBE. Moreover it is demonstrated how the use of a rubber based fail safe system reduces the impact forces.

An analysis of documents describing the following events has been performed (task 5.6):
- Flood of Mississippi river affecting Fort Calhoun nuclear station in June, 2011.
- Earthquake and tsunami affecting Fukushima Dai-Ichi nuclear site in March, 2011.
- Earthquake and tsunami affecting Fukushima Dai-Ini nuclear site in March, 2011.
- Earthquake and tsunami affecting Onagawa nuclear site in March, 2011.

On the basis of the abovementioned documentation an optimized plant layout for the mitigation of seismic effect has been studied, taking into account the general safety approach which foresee that at system and components shall be assigned safety class and seismic category according their importance and function. In this studies, the plan layout has not been evaluated minimizing the seismic response acceleration only (deeply studied in the WP2 and WP3) by the suitable design of seismic isolation, but considering also the fully redundancy and independence features of the main NPP components that must be maintain also during seismic event.

The main principle for a correct design of the civil works, piping and equipment have been also outlined. In order to minimize the seismic effect for the ELSY and MYRRHA reactor, some recommendations for the plant layout have been proposed.

WP6 was aimed to develop recommendations for mitigating the risks due to external accidents on liquid metal pool type reactors. Attention was paid to the evaluation of the benefits in terms of economics derived
from the mitigation of the failure risk related to earthquakes and earthquake-induced phenomena as well as from the high level of standardization derived from the plant isolation. A specific objective was the knowledge transfer on external risk mitigation to Gen III LWR technologies.

The economics of isolated systems has been studied (Task 6.1). The conclusion has been that economics are not a decisive factor in the choice of isolated or non-isolated NPPs. The safety gain through isolation makes the difference. Overall it has to be assessed that providing base isolation to a nuclear power plant does not provide a financial risk on the investor. The technological disadvantages are considered to be manageable. All kinds of cases and scenarios for isolated versus fixed base foundations have been studied and compared. It has been found that the upper limit is additional costs in the order of 2%, whereas in the best case some 5% of the total costs can be saved. It further has been demonstrated that the costs of the isolation itself are between 1 and 2% of the total costs only which can easily be compensated by the gain of safety and related overhead cost issues. There is no additional demand on maintenance anticipated for the isolated case. Nevertheless should it be necessary to add maintenance routines they would only marginally increase the operation costs. Overall it has to be assessed that providing base isolation to a nuclear power plant does not provide a financial risk on the investor. The technological disadvantages are considered to be manageable.

Activities have been carried out to develop guidelines (task 6.2). The developments of codes on ISO level (i.e. ISO 55000 Asset Management and ISO 31000 Risk Framework) provide a new generic approach to this important subject and brings added value into the nuclear sectors practice. The mathematical formulation of ageing and the coming new Eurocode on Risk based inspection will also provide considerable improvement of risk related procedures in the industry. The nuclear sector is very well organized in terms of guidelines and standards. The work focused on those points of interest which are not yet covered by the existing regulations. The work therefore concentrated on:

The nuclear regulatory environment.
The specification of the new elements (isolators).
The risk framework and assessment.

It has to be noticed that guidelines are long term objectives and activities that cannot be seen isolated in short research projects. The work was focused on bringing the sector forward in the right direction. A report has been issued that describes the recommendations for the design, manufacture and testing of pipeline expansion joints that are suited to compensate for the relative displacement between isolated and non-isolated structures of an NPP during a seismic attack, whereby:
 recommendation regarding the design and manufacture and recommendations outlining standard procedures for pipes and pipe expansion joints seismic testing are proposed.
a monitoring systems to measure the deformations of the isolators and the acceleration of the isolated buildings of a NPP during earthquake is studied. Reference is done to ELSY and MYRRHA systems, but results are applicable to any kind of isolated NPPs.
the main procedures for the design, manufacturing, qualification, factory production control, installation and maintenance of seismic isolators for NPPs are summarised.

Reference are made mainly to the Harmonized European Standard EN 15129 Anti-seismic devices, approved by CEN in November 2009. This Standard, which became effective and mandatory on August
1st, 2011, with the related CE marking, is not specifically addressed to nuclear plants, and thus these guidelines will suggest extensions and additional clauses for NPPs to be included during its revision process.

Knowledge transfer has been continuously performed throughout the project. The knowledge on Generation III reactors has been well represented in the consortium and the ideas have always been tested against the new development. An analysis of Gen III technologies has been carried out (task 6.3) leading to the conclusion that those technologies answered to particular specifications of the SILER project but they can be adapted for use in Light Water Reactors (LWR) or Sodium Fast Reactors (SFR), depending on the soil type, seismic region, plant design and reactor type.

WP7 was devoted to the dissemination of knowledge and education.

A website (www.siler.eu) has been created (task 7.1) and organized as follows:

a) an home page, describing the Project objectives and structure.

From the home page, different areas can be accessed:

b) a detailed description of the work packages;

c) the list and description of project partners;

d) an area where the Project results are summarized at the end of the Project duration;

e) an open documentation section, where all the public deliverables, the presentations, the papers and, in general, the whole open documentation produced during the Project duration have been published;

f) a section dedicated to the project events, as the training course, the international workshops and all the other events organized in the frame of the Project.

Thanks to its features of portability and accessibility of the information, the SILER official website has registered a mean of 800 visits per month, coming from all over the world (EU, US, China, etc...).

An international workshop has been organized in Italy, on June 18-19th, open to all experts in seismic isolation (thus not only related to GEN IV reactors) in order to exchange experience (task 7.2).

Five main topics have been treated:

- Modelling of systems & isolators for dynamic analyses;
- Development, fabrication & testing of isolation systems;
- Sloshing in seismic isolated reactors;
- Design guideline & economics for seismic isolated systems;
- Interconnection systems for seismic isolated systems.

A call for papers has been launched and drafting instructions, including a MS-Word template for the draft paper, have been provided to the participants.

32 researchers, coming from ten different countries (two outside the EU, USA and ROK; eight from the EU: AT, BE, FR, GE, IT, SE, SP and UK) participated in the workshop, with a good balance between the SILER-partners and the rest of the world.

The workshop has been the opportunity for deep discussions on seismic isolation techniques and modelling. SILER results were found very interesting by the outside world. Outside information could be gathered, determining the success of the event.
PhD thesis topics have been set up (task 7.3) on the basis of which the PhD students have been carried out their work.

PhD thesis title were:

"Analysis of Risk of Seismic Initiated Events in Metal Cooled Fast Reactors".
"Evaluation of the dynamic coupling phenomena between the main components of a lead-cooled reactors, including the sloshing effects and seismic insulation systems. Identification and evaluation of the technical solutions able to mitigate the seismic effects on the most critical reactor systems".
"Modelling of fluid structure interaction in sloshing flows, with application to Lead Fast Reactors (LFR) ".

An international educational workshop has been organized in Rome on September 24-25th 2014 for permitting to the PhD students to present their work. The agenda of the educational workshop was as follows:

September 24th
11:15 Welcome (Giuseppe Moretti, SRS, Walter Villanueva, KTH and Antonio Moreno, IDOM)
11:30 Summary of the SILER Project (Massimo Forni, ENEA)
12:15 Future of LFR in Europe: the ALFRED reactor (Luigi Mansani, ANSALDO)
13:00 Lunch
14:30 Present status of MYRRHA and future developments (Didier De Bruyn, SCK-CEN)
15:15 Seismic Isolation of Nuclear Installations in France (Pierre Sollogoub)
16:00 Coffee break
16:30 Notes on the activities of the University of Rome aimed at enhancing the safety of liquid metal cooled and small modular nuclear reactors (Antonio Naviglio, University of Rome)
17:15 Identification and evaluation of the technical solutions able to mitigate the seismic effects on the most critical reactor systems (Matteo Nobili, University of Rome)
18:00 Adjourn

September 25th
09:30 The evolution of Graphic Process Unit computing in the context of Smoothed Particle Hydrodynamics simulation (Josè Luis Cercos-Pita, UPM)
10:15 Smoothed Particle Hydrodynamics simulations of a sloshing phenomenon loads inside a nuclear reactor due to earthquake movements (Pasquale Dinoi)
11:00 Coffee break
11:30 Research activities of KTH on safety and thermal-hydraulics of heavy liquid metal (HLM) systems (Walter Villanueva, KTH)
12:15 Parametric Study of Sloshing Effects in the Primary System of an Isolated Lead-Cooled Fast Reactor (Marti Jeltsov, KTH)
13:00 Lunch
14:30 Seismic vulnerability assessment of nuclear systems and civil structures according to nuclear standards and codes (Pasquale Palumbo, SOGIN and Giuseppe Moretti, SRS)
15:15 Recent applications of seismic isolation to nuclear plants: Jules Horowitz Reactor and ITER (Sebastien Diaz, NUVIA)
16:00 Tests on full-scale prototypes of high damping rubber bearings and lead rubber bearings for nuclear applications (Maria Gabriella Castellano, FIP)
16:45 Discussion
17:30 Closure

The original contributions have been posted as pdf files on the public part of the SILER website.
A training course on Seismic Issues in NPPs has been organized (task 7.4) with the aim of giving a base of knowledge to deal with the issues of seismic behavior and risk mitigation in NPPs, with particular attention to lead cooled systems. The training course was addressed to PhD students and researchers active in the field.

The course has been held in Verona, at Palazzo Camozzini, in the city centre, from May 21st to 25th 2012.

A visit to FIP Industriale laboratories has been held on May 23rd.

The programme of the course was as follows:

- **Presentation of the SILER Project**
  - Silvia De Grandis, SINTEC (Bologna, Italy), Management Officer of SILER
- **ELFR, the European Lead-cooled Fast Reactor**
  - Luigi Mansani, ANSALDO (Genova, Italy)
- **MYRRHA, the Multi-purpose Hybrid Research Reactor for High-tech Applications**
  - Didier De Bruyn, SCK•CEN (Mol, Belgium)
- **Nuclear installations – Issues and trends in seismic hazard and fault capability evaluation**
  - Raffaele Figini, ENEL (Rome, Italy), Member of the SILER EAC
- **General overview on the Gen IV Lead-cooled Fast Reactors and the new requirements for safety**
  - Craig Smith, Naval Postgraduate School, NPS (Monterey, USA), Member of the SILER EAC
- **The damaging effects of earthquakes on conventional facilities**
- **The damaging effects of earthquakes on NPPs**
  - Antonio Moreno, IDOM (Madrid, Spain)
- **Seismic Isolation: state of the art of applications to Nuclear Power Plants**
  - Massimo Forni, ENEA (Bologna, Italy), Coordinator of SILER
- **IAEA programme on Fast Reactor Technology**
  - Stefano Monti, IAEA (Vienna, Austria), Member of the SILER EAC
- **Testing of large scale anti-seismic devices**
  - Gianmario Benzioni, University of San Diego (USA), Member of the SILER EAC
- **Visit to FIP industrial laboratories, including the presentation “Anti-seismic devices”**
  - Maria Gabriella Castellano, FIP Industriale (Selvazzano, Italy)
- **Special issues on seismic isolation**
  - Ioannis Politopoulos, CEA (Paris, France)
- **How to isolate a NPP - general overview**
  - Sébastien Diaz, NUVIA (Lyon, France)
- **How to isolate a NPP - interface components: piping joints**
  - Helmut Novak, BOA (Stutensee, Germany)
- **How to isolate a NPP - interface components: seismic joints**
  - Robert Gettert, MAURER (Munchen, Germany)
- **How to isolate a NPP - interface components: fail safe system**
  - Alberto Dusi, NUMERIA (Cremona, Italy)
- **Testing of Interface Components**
  - Pierre Pegon, JRC (Ispra, Italy)
- **Finite Element Modeling and dynamic analyses of isolated NPPs**
  - Francisco Beltran, IDOM
- **Fragility Analysis of isolated NPPs**
Federico Perotti, POLIMI (Milano, Italy), Member of the SILER EAC
Severe accidents and seismic issues in lead-cooled systems
Donella Pellini, KIT (Karlsruhe, Germany)
Modeling of liquid metals and analysis of the sloshing effects
Armando Gabino, IDOM (Madrid, Spain)
Gas Entrapment and fluid-structure interaction
Pavel Kudinov, KTH (Stockholm, Sweden)
Economics of isolated NPPs
Helmut Wenzel, VCE (Vienna, Austria)

Potential Impact:
The leading position of Europe in nuclear science and technology is worldwide acknowledged, as well as its renown engagement in pursuing a sustainable and secure energy strategy of which nuclear is expected to play a significant role, as stated in the Strategic Energy Technology Plan. While in the short term a progressive improvement of the present technology, through evolutionary power plants, is pursued, the long term actuation of this strategy requires steep innovations leading to a new generation of nuclear energy systems, for which a thorough R&D campaign is already started, leading to the identification of three promising candidate technologies based on Sodium-, Lead- and Gas-cooled Fast Reactors.

Focusing on Lead-cooled systems, it has to be noticed that many R&D organizations and industries within the EU are conducting strong R&D in the development of Generation IV Lead-cooled reactors (LFR) and of Transmutation Devices (ADS) with substantial support from EURATOM. This research effort has permitted significant technology advancement achieved in the past years, that have toughened the reliability on this emerging solution, raising more and more interest in the potential improvements that are allowed by the use of lead as coolant, notably to what concerns a) the potentially unprecedented safety levels through inherent and passive features, b) the highest sustainability achievable, extending by a factor $\approx 100$ the fuel resources and minimizing the volume and long term radiotoxicity of the waste to be disposed of (hence, simplifying the management of the final waste through the reduction of the required monitoring period to technologically feasible and manageable time scales) and c) the perspective for economic competitiveness through relevant simplifications of the plant design. In September 2007, then, to focus and streamline the efforts, a Sustainable Nuclear Energy Technology Platform (SNE-TP) was launched in Brussels, through which the European research nuclear fission community joined its efforts to issue a Strategic Research and Innovation Agenda (SRIA) for achieving sustainable nuclear fission energy.

The SRIA, updated in 2013, outlines the R&D roadmap for the development, among other, of fast neutron lead cooled systems, considered in the Generation IV Technology Roadmap as very promising technologies.

SILER Project has, then, a strong impact on the implementation of the SRIA for what concerns the development of LFR systems, which strongly depends on developing, demonstrating, and deploying advanced designs that exhibit, among other, excellent safety characteristics and an high level of technology readiness.

The Project showed also strong synergies with other EU research activities (many of them funded by 7th FP) and in particular with the LEADER Project, aimed to develop at a conceptual level a Lead Fast Reactor Industrial size plant and a scaled demonstrator of the LFR technology, as well as with the several
Project dedicated to the development of a LBE-cooled ADS. The strong integration among the different Projects research teams had a large, positive impact on the SILER implementation as well as it favoured a wide dissemination of the Project results.

The designs of the abovementioned systems nuclear plants ask continuously for safety improvements, also based on the experience on the existing plants behaviour under damaging events.

For Generation IV reactors maintaining and enhancing the safe and reliable operation is an essential priority in the development. Safety and reliability goals broadly consider safe and reliable operation, improved accident management and minimization of consequences, investment protection, and reduced need for off-site emergency response.

Generation IV reactors have, then, to be highly secure and designed to withstand external events such as earthquakes, floods, tornados, plane crashes, and fires. Their features has to considerably reduce the impact of external or internal threats through the redundancy, diversity, and independence of the safety systems as well as through a specific design of critical components and the adoption of protective measures (i.e. seismic isolation). This goal, strongly outlined in the GIF roadmap, points out the need to increase public confidence in the security of nuclear energy facilities.

SILER Project had, then, a strong impact on the overall success of the development program of LFR and ADS systems, thanks to its contribution to developing, demonstrating, and deploying advanced designs that exhibit, among other, excellent safety characteristics.

The approach followed within the project had an impact also on giving indication on several aspects on which focusing the activities and on supporting the identification of research priorities to answer relevant questions arising from advanced design for enhanced safety, in order to permit the timely development of LFR and ADS systems as foreseen in the SRIA.

The structure of the project permitted to play a positive role in the implementation on the SRIA from one hand and consented to contribute to the competitiveness of European key players (e.g. Industries, Research Associations, etc.) in this field, also facilitating cooperation and spread of results and dissemination of information. SILER, in fact, with its specific work package dedicated to dissemination, contributed to the circulation of information on the selected technologies creating links among different teams. Moreover, with the training task it contributed to the growing-up of a young generation of future experts in the field that will form the human potential for the design/construction/operation of next generation nuclear plants.

Moreover, in addition to the impact on the research community, the Project had a positive impact also on the Public at large.

SILER, in fact, had an impact on the public concerns related to nuclear energy in general, given the fact that it address the issue of safety, that it is of paramount interest also outside the community of researchers directly involved in nuclear field. The continuous enhancement of the safety level of present and future nuclear power plants has always been a priority in the EU research programmes, and it assumed a paramount relevance after the Fukushima events, following also the trend dictated by the IAEA Action Plan for making nuclear energy safer. In this sense, the impact of SILER, that specifically addressed the issue of seismic risk mitigation, is expected to be extremely positive for widening the public acceptance of nuclear technology.
It has to be noticed that the need of innovative design solutions and technology features to achieve high level of safety and security it is clearly expressed in the STE-TP SRIA, also to improve economic competitiveness. In this sense, SILER, with a deep examination of risks associated to external events on LFR and ADS component, the design of specific critical components, the study of specific layout solutions, the development of advanced isolators, the issuing of guidelines and recommendations for standardization as well as thanks to economic analysis impacted strongly on one of the critical issues recognized by the SRIA in the development pat of next generation nuclear systems, the economic competitiveness. Particular attention has been given in fact, in the Project, to the aspect of economics. Attempts to standardization are made in the Project, so to reduce the costs of the selected technologies. Moreover, in general, supporting the development of lead-cooled systems, SILER Project addresses aspects impacting on the economic attractiveness of future generation nuclear energy systems, i.e.: lead-cooled systems have the potential for lower capital costs with respect to other fast spectrum reactors due to the elimination of the intermediate cooling circuit and the great simplification of the primary system, making these systems competitive with respect to present generation LWRs; the enhancement of the safety aspects of the systems will provide a measurement of their reliability, reducing the uncertainties and drawing a clearer picture of the safety provisions to be foreseen, hence allowing a reduction of the costs while ensuring higher and higher effectiveness.

Moreover, the standardization introduced with the seismic isolation will permit to transfer the Project results also to other technologies (i.e. Generation III LWRs), in accordance with the goals of the SNE-TP SRIA., with a positive economic impact. In general, the activities carried out have been relevant for several systems among those chosen within Generation-IV and presently under investigation within several projects financed by the EU, as already mentioned.

SILER Project impacted also on the EU strategy for a long term sustainable energy production: supporting the lead technology, providing design of seismic isolators for both the LFR and ADS systems, SILER facilitates the achievement of the aimed low carbon economy by 2050.

Finally, the Project had also a wide societal impact: the low costs for electricity envisaged by lead-cooled system will make energy easily and fairly available to everybody, so will help to reach a situation where the obstacles potentially implicated by the large deployment of other, costly energy sources are levelled, facilitating the accessibility to high-quality life conditions.

List of Websites:
www.siler.eu

Contact details:
Coordinator: Massimo Forni, ENEA, Via Martiri di Monte Sole 4, Bologna, Italy.
Tel. +39 051 6098554
Email: massimo.forni@enea.it

Letzte Aktualisierung: 8 Mai 2015
Aktenzeichen: 163358