Seismic Isolation of Nuclear Power Plants

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SUMMARY
The paper presents the world state-of-the-art of the Nuclear Power Plants (NPPs) provided with seismic isolation and focuses on the main problems related to the application of this technology to so peculiar structures, characterized by high masses, large sizes and severe safety requirements due to the possibility of relevant accidents with release of radioactivity and other extremely dangerous materials.
Difficulties in the application of seismic isolation to NPPs are mainly due to the lack of specific standards and to the need of manufacturing quite large isolators (and test them in extreme multidirectional dynamic conditions), and using interface components, like pipe expansion joints for hot and pressurized pipelines, capable of absorbing the large relative displacements which occur between the isolated nuclear island and the ground during the seismic attack.

Keywords: Seismic isolation, Nuclear reactors, Anti-seismic engineering

1. INTRODUCTION

Nowadays, seismic isolation is widely used to protect not only civil buildings but also bridges, viaducts and industrial plants (there are 10,000 applications, approximately, all over the world, as stressed by Martelli et al., 2012), and is considered one of the most promising technology to protect nuclear reactors from violent earthquakes. In spite of this, only two nuclear plants are currently provided with base isolation: 4 PWRs (Pressurized Water Reactors) at Cruas (France) and 2 PWRs at Koeberg (South Africa). In addition, the Jules Horowitz Reactor (JHR), now under construction at Cadarache (France) with a seismic isolation system similar to that of Cruas, must be cited.
The extremely limited number of existing isolated nuclear plants is probably due to the fact that most of them are water reactors, which are characterized by quite stiff structures and rigid components, with an intrinsic robustness sufficient to resist to the relatively low seismic inputs assumed as design for most of the Generation II reactors in the '70s and '80s (0.2÷0.3 g peak ground acceleration, typically). As a matter of fact, among the new designs of water reactors, only IRIS (International Reactor Innovative and Secure) and 4S (Super Safe, Small and Simple) are provided with base isolation.
On the contrary, among the fast reactors, most of the recent designs already include seismic isolation: ALMR (Advanced Liquid Metal Reactor), S-PRISM (Power Reactor Innovative Small Module), KALIMER (Korea Advanced LIquid MEtal Reactor), DFBR (Demonstration Fast Breeder Reactor), STAR-LM (Secure Transportable Autonomous Reactor-Liquid Metal) and EFR (European Fast Breeder Reactor). In fact, these reactors are characterized by quite flexible internal components, particularly prone to amplify the seismic excitation.
Unfortunately, no application of the abovementioned reactors has been done, yet, and there is a dramatic lack of information and experimental results about the behaviour of large isolators under severe dynamic conditions. In addition, no specific standards are available up to now for the application of seismic isolation to NPPs, in Europe and USA, at least.

2. STATE OF THE ART OF ISOLATED NPPS

2.1. Application to Light Water Reactors

The first application of seismic isolation to a nuclear power plant was completed at Cruas, France where 4 PWRs (with a total electric power of 3600 MWe) were isolated at the end of the '70s (the construction began in 1978 and the reactors became operative between 1983 and 1984). The choice of seismic isolation was done to keep the design unchanged with respect to other reactors already designed or built by EdF in France, in places with lower seismicity (typically 0.2 g peak ground acceleration, being 0.3 g that of Cruas). For the same reason, two 900 MWe PWR units (same model of Cruas), were provided with seismic isolation in Koeberg, South Africa. The construction began in 1976 (even before than Cruas) but the reactors were completed in 1984-1985.

The isolation system of Cruas consisted in 3600 square neoprene bearings (900 for each unit, 500x500x66 mm size). The isolators of Koeberg (again 900 for each unit, but 700x700x130 mm size) have been coupled with sliding pads to limit the stress in the neoprene at high shear strains.

In addition to the Cruas and Koeberg NPPs, it must be cited, among the "nuclear" applications, the isolation of an "uranium enrichment facility" in France, three pools for spent fuel elements at La Hague (France) and a nuclear fuel related facility in Japan, consisting in a five storey building (owned by the Japan Nuclear Cycle Development Institute) isolated with 32 Lead Rubber Bearings (LRBs).

It is worth noting that the first new application after Cruas and Koeberg, is represented by the Jules Horowitz Reactor, now under construction at the Cadarache Nuclear Centre site (France) with an isolation system composed by 195 neoprene bearings (900x900x181 mm size, manufactured by NUVIA, Freyssinet Group) already installed, see Fig. 1). In addition, the ITER (International Thermonuclear Experimental Reactor) will be erected soon with base isolation, again at Cadarache.

Among new water reactor designs, the 4S (Super Safe, Small and Simple) reactor, developed by Toshiba-Westinghouse, is in advanced development phase. A first unit of 10 MWe provided with base isolation should be built in the high seismicity site of Galena (Alaska), but the reactor is not licensed by the NRC (Nuclear Regulatory Commission), yet. The isolation system is composed by 20 LRBs; the horizontal natural frequency of the isolated system is 0.5 Hz. The design of the 4S seismic isolators shall be in accordance with Japan Electric Association Guide JAEG 4614-2000, "Technical Guideline on Seismic Base Isolated System for Structural Safety and Design of Nuclear Power Plants." Toshiba has also prepared guidelines for Quality Control and Maintenance Control of seismic isolation devices which are based on the "Draft Technical Guidelines for Seismic Isolation of fast breeder Reactors" that were developed in the "Verification Test of the FBR Seismic Isolation" study conducted by the Central Research Institute of Electric Power Industry (CRIEPI) from 1987 through 1996. It is worth noting that the above guidelines are the only standards now available in the world for seismically isolated nuclear plant. Unfortunately, as far as the authors know, no English translation of this document is available.

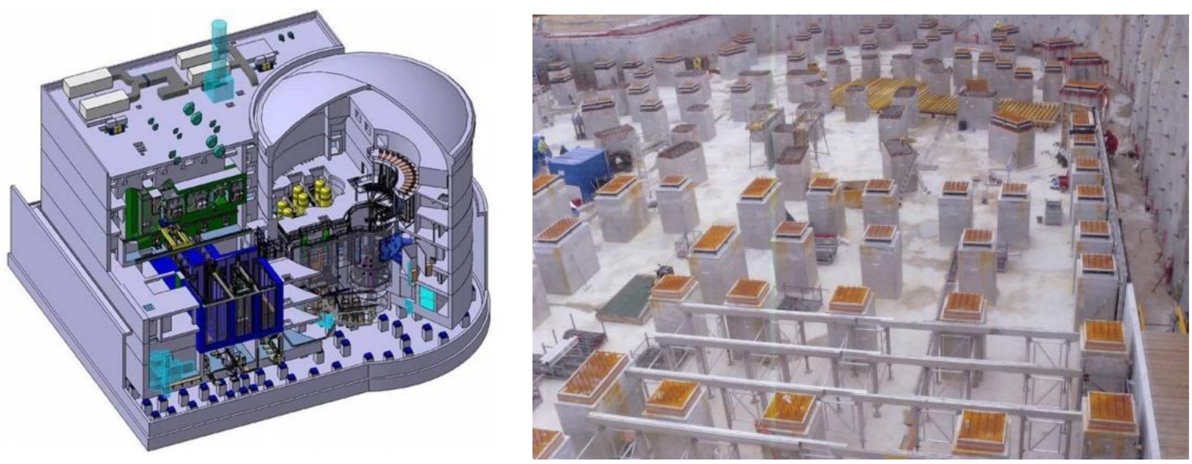

Figure 1. Sketch of the Jules Horowitz reactor and view of the isolation system during installation.

2.1.1. The IRIS

The case of the IRIS (International Reactor Innovative and Secure) is analyzed more in detail, due to the huge amount of numerical analyses and experimental tests carried out in the last years by the authors of this paper. IRIS has been developed by an international team led by Westinghouse (who, however, recently left the group). ENEA had an active role in the IRIS team and proposed the seismic isolation of the whole reactor building in 2006. The proposal was accepted and seismic isolation became the reference design solution for IRIS since 2008 (independently of the construction site). From 2006 to 2010 ENEA, in cooperation with Politecnico di Milano and Pisa University, developed an isolation system composed by 99 High Damping Rubber Bearings (HDRBs) which gives to the isolated building a natural frequency of 0.7 Hz. The isolators are made of hard rubber compound (shear G modulus = 1.4 MPa) and have diameters equal to 1 and 1.2 m. The total rubber height is 10 cm, corresponding to the deformation at SSE (0.3 g PGA).

Lots of numerical analyses carried out on detailed reactor building models showed the excellent behaviour of the reactor in the isolated conditions. In particular, the acceleration is dramatically reduced with respect to the fixed base configuration (in the horizontal direction at least) and that the isolated building behaves practically like a rigid body. Thus, all the equipments and components of the plant are subjected to the same horizontal acceleration, independently of their position in the building. Of course, this simplifies a lot the design activity and allows for a standardization of the plant, whose design become independent of the seismicity of the construction site (still unknown).

The IRIS seismic design activity was concluded in 2010 with the design, manufacturing and testing of half scale samples of the lower size isolators. The experimental tests showed an excellent behaviour of the isolators (manufactured by FIP Industriale, Italy), which begun to damage beyond 300% shear strain (a deformation 3 times higher than the design value calculated at SSE).

Finally ENEA, as consultant of Westinghouse, also begun the licensing process of the isolation system at NRC (which is complicated by the fact that, as already mentioned, no standard exists, in both USA and Europe, regarding the seismic isolation of NPPs).

Additional information of the IRIS isolation system are provided by Forni et al. (2009) and by Bergamo et al. (2011).

2.2. Application to fast reactors

No fast reactor is currently provided with base isolation. However, most of the recent designs foresee this solution to mitigate the earthquake effects, especially those which have to fulfil the severe requirements of GEN IV reactors. It is worth noting that seismic loads are more important for fast reactors, due to the architecture of the plant, which is characterized by heavy and flexible structures. Particular attention must be paid to sloshing effects when the pool type solutions is adopted (especially for lead cooled reactors).

The ALMR (Advanced Liquid Metal Reactor) is a sodium reactor developed by General Electric-Hitachi Nuclear Energy in the 80’s; the project was sponsored by U.S. Department of Energy (DOE). The ALMR isolated structural configuration consists of a stiff steel-concrete box structure, which supports the reactor vessel, the containment dome, and the reactor vessel auxiliary cooling system stacks. The total isolated mass is about 23,000 t, supported by 66 high damping rubber bearings made of hard compound (shear modulus G=1.1 MPa). The Safe Shutdown Earthquake (SSE) is characterized by an horizontal and vertical peak ground acceleration (PGA) of 0.5g. The horizontal isolation frequency is 0.7 Hz, and the vertical frequency is greater than 20 Hz. ENEA participated in the verification of the design of the isolators.

The S-PRISM (Power Reactor Innovative Small Module) is a modular reactor (415 MW for each module), again developed by GE in the 80’s. Of course, for this kind of reactor the standardization of the design is a very critical issue. Seismic isolation was considered the most promising solution to keep the design unchanged independently of the construction site. The reactor module was supported by 20 HDRBs which give to the system an horizontal frequency of 0.7 Hz (21 Hz in the vertical direction, which is not isolated) and provide a reduction of the horizontal shear forces by a factor 3. The PGA was 0.5 g at the SSE. It is worth noting that this project was abandoned in 1994 before obtaining the licensing and now a new design, including seismic isolation, is in progress and aims to satisfy the severe requirements of GEN IV reactors.

For the STAR-LM (Secure Transportable Autonomous Reactor-Liquid Metal) reactor, now under development at the Argonne National Laboratory (ANL), the standardization of the design is a key issue even more important than for S-PRISM, also due to the severe requirements of GEN IV for lead reactors. The SSE and OBE are characterized by a PGA of 0.3g and 0.2 g, respectively. The isolation system is made of cylindrical isolators with a diameter of 1.2 m and a rubber height of 0.5 m; the isolation frequency is 0.5 Hz in the horizontal direction and 21 Hz in the vertical one. For this reactor, a study for the seismic isolation in the vertical direction (with a frequency of 1.1 Hz) is being carried out. The problems related to the isolation of a structure in the vertical direction is stressed in § 3.3.

The KALIMER (Korea Advanced LIquid MEtal Reactor) is an economically competitive, inherently safe, environmentally friendly, and proliferation-resistant sodium cooled reactor which is now being developed by the Korea Atomic Energy Research Institute. A total of 164 HDRBs (1.2m diameter) are installed between the ground and the lower base mat in the KALIMER-600 reactor and fuel handling buildings. The seismic gap between the isolated reactor building and the non-isolated wall is about 1.2 m, sufficient to avoid contacts ("hammering") even when the plant is subjected to a beyond design earthquake with a peak ground acceleration of 1.0 g.

Studies for the seismic isolation of fast reactors began in Japan in the 90's on the DFBR (Demonstration Fast Breeder Reactor). The reactor building of DFBR-1 adopts a seismic isolation made of 175 LRBs with a vertical load of 10,000 kN. The design guidelines for seismic isolation were drafted by CRIEPI and required that deformation of the isolators remained within 2/3 of the linear deformation limit. It is worth noting that, for the DFBR, the possibility to isolate the reactor building in the vertical direction trough air springs was evaluated. A new generation of Fast Breeder Reactor is now under development in Japan, with an only horizontal seismic isolation made of LRBs having a diameter of 1.6 m. Scaled samples of such devices have been tested on the large shaking table of the E-Defense of the National Research Institute for Earth Science and Disaster Prevention of Japan. As for the case of 4S reactor, reference was made to the "*Technical Guidelines on Seismic Base Isolation System for Structural Safety and Design of Nuclear Power Plants*".

Also for the EFR (European Fast Breeder Reactor) studies on seismic isolation begun in the 90's and regarded the whole reactor building in the horizontal direction, and the tank also in the vertical one. At present, the ESFR (European Sodium Fast Reactor) is under development in the framework of the European Collaborative Project CP-ESFR, with the aim of evaluating pros and cons of the loop and pool solutions. In this project, ENEA is responsible of the task *Design measures for consequence mitigation of seismic loads*, in the framework of which the seismic isolation of the whole reactor building has been proposed. Aim of the task is also the development of guidelines and recommendations to provide techniques and methods for the reduction of seismic vulnerability.

Finally, it must be cited that, in the framework of the SILER Project, studies are in progress to isolate two Gen IV lead fast reactors: the European Lead Fast Reactor (ELFR, former ELSY) and the Multi-purpose hYbrid Research Reactor for High-tech Applications (MYRRHA), as described by Forni and De Grandis (2012).

Additional information about seismically isolated NPPs is provided by Forni et al. (2011).

3. SEISMIC ISOLATOR TYPOLOGIES

A seismic isolator (acting in the horizontal directions only) is a device that must:

1. Support the dead load;
2. Allow horizontal deformations.

Thus, a seismic isolator is, first of all, a bearing (condition 1), because it must carry the dead load of the structure for all its life; therefore, it must satisfy all the typical requirements of bearings. In addition, a "good" seismic isolator shall have the following two characteristics:

3. Provide a restoring force;
4. Dissipate energy.

The restoring force reduces the deformation during the earthquake and the offset at the end of the seismic motion. The energy dissipation reduces the deformations during the earthquake. High

Damping Rubber Bearings (HDRBs) and Lead Rubber Bearings (LRBs) are the most diffused seismic isolators in the world.
Other kind of isolators, like sliders (with both flat or curved surfaces) or rolling devices, are not suitable for application in NPPs, especially due to the lack of information about the long term behavior of the friction coefficient of the sliding surfaces.

3.1. High Damping Rubber Bearings

HDRBs are composed by alternate rubber layers and steel plates, bonded together during the vulcanization phase of the isolator. HDRBs have all the four abovementioned mentioned characteristics of the isolator, as stressed below.
The capacity of supporting the axial (vertical) forces is given by the reinforcing steel plates which hinder the radial deformation of the rubber.
Horizontal (shear) deformations are allowed by the elasticity (or, better, hyper-elasticity) of the rubber, that also provides the restoring force. The shear modulus (G) of the rubber ranges between 0.4 MPa (soft compound) to 1.4 MPa (very hard compound). For civil building applications, a medium compound (G=0.8 MPa) is often used. For nuclear applications, due to the large masses to be isolated (and, consequently, the high stiffness needed), the hardest compound is often necessary. In this case, particular attention must be paid to the bonding between rubber and steel. Finally, the energy dissipation is obtained by using suitable chemical components in the rubber compounds; the equivalent viscous damping can range from 5% (natural rubber) to 15% (high damping rubber). It is worth noting that higher is the damping factor, lower is the failure limit of the isolator. Typically, natural rubber and high damping rubber fail beyond 500% and 300% shear strain, respectively. If higher damping values are needed, the use of lead rubber bearings is recommended (see § 3.2) instead of additional energy dissipaters.
As stressed above, the isolators used for nuclear application are usually quite large, due to the high mass of the superstructure. This introduce difficulties in the manufacturing process. In fact, the abovementioned vulcanization phase requires a quite uniform temperature distribution in the whole isolator, which is more difficult to be obtained for large volumes. Thus, particular attention must be paid to the production process controls and in the qualification of the device.

3.2. Lead Rubber Bearings

The insertion of one or more lead cores within a rubber bearings can increase the equivalent viscous damping of the isolator up to 25-30%. The advantage to dissipate energy trough the lead core is that the isolator can be made in low damping natural rubber, which is more resistant to failure, as stressed in § 3.1. The disadvantages are a more difficult manufacturing process and a lower re-centring capability. LRBs are more diffused in Japan; as reported above, they are foresee for the seismic isolation of the 4S water reactor and for the Japanese FBR.

3.3. Vertical isolators

One of the most important advantages of the isolation of a nuclear reactor is the possibility of standardizing the design, which could become independent of the seismicity of the construction site. Of course, a complete standardization should have to include also the vertical component of the earthquake. Unfortunately, the isolation of an object in the vertical direction involves extremely high technical difficulties, especially in the case of heavy and high structures as the NPPs. In fact, the introduction of the vertical degree of freedom also introduces the rotation of the isolated structure around the two horizontal axes, which is very difficult to control due to the high overturning moment.
Only preliminary studies were performed on isolated nuclear plants in vertical direction; they are mainly carried out in Russia and Japan (see § 2.2 for STAR-LM and DFBR) and foresee the use of air springs. It is worth noting that the horizontal seismic isolators do not directly amplify the vertical acceleration of the earthquake. However, they introduce in the reactor building base raft (which is now suspended and not continuously in contact with the ground like in the case of fixed base), additional vibration modes characterized by relatively high natural frequencies (say 20-30 Hz) active in the

vertical direction. Thus, the use of horizontal isolators could "create" some "new" vertical excitations, especially in case of large isolated structures with relatively "thin" base raft and wide isolator distance. The dynamic behaviour of critical components sensible to the vertical accelerations, as for example electrical/electronic equipments or wide-span pipelines, must be carefully analyzed. If necessary, these components can be provided with suitable devices, composed by springs and/or dashpots acting in the vertical direction, capable to damp and limit the oscillations.

4. INTERFACE DEVICES

The adoption of base isolation introduces significant relative movements between the isolated and non isolated parts of the plant. Thus, a seismic gap must be present all around the isolated part and shall be adequately protected (§ 4.1) and kept free during the whole life of the structure, in order to allow the relative movements in case of earthquake. All the service networks and pipelines crossing the seismic gap shall be provided with suitable expansion joints (§ 4.2). In case of beyond design earthquakes, the deformation of the isolators could even exceed the width of the gap. To guarantee a relatively soft hammering between the isolated structure and the lateral containing wall of the foundation, an horizontal fail safe system provided with a damper can be installed (§ 4.3).

4.1. Seismic gap

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

4.2. Expansion joints

For the regular service networks (pipes, wires and cables) several kind of expansion joints are already available on the market, used in the isolation of civil buildings, and no particular design solutions are necessary for applications in nuclear plants. When the whole nuclear island is isolated, one of the most critical systems crossing the seismic gap is the pipeline which goes to the turbines (containing hot and pressurized steam). Expansion joints similar to those needed in this case were tested in the framework of the INDEPTH project (ENEL.Hydro et al., 2002) for an isolated tank of a petrochemical plant. The technology for this kind of devices already exists also for high temperatures and pressure. It is worth noting that a smart disposition of two gimbals and one angular joints along the pipeline provide six degree of freedom to the system and can accommodate even huge displacements with very limited rotations (and then stresses) of the joints.

4.3 Horizontal fail safe system

Even in case of beyond design earthquakes, the isolators shall never loose the capability of supporting the vertical load. Thus, the adoption of an horizontal fail safe system to limit the isolator deformation must be foreseen. It is also strongly recommended that the fail safe system includes some shock absorber (for example a rubber bumper) to soft the hammering between the isolated building and the foundation. These devices are not present in the Cruas, Koeberg and Jules Horowitz Reactors, and are seldom used in civil buildings.

5. STANDARDS AND GUIDELINES

The design and construction of nuclear plants are regulated, all over the world, by well known

standards (issued by the NRC, IAEA, JAEA, etc.) that also include the seismic conventional design, but without seismic isolation. Moreover, there are several standards for the design and construction of isolated civil buildings like EURODE 8 and others. Finally, there are some standards addressed to the design, manufacturing and testing of seismic isolators for civil applications, like EN 15129, which came into force in 2010 in all European countries (see § 5.1). But no standard, at present, is specifically addressed to seismically isolated nuclear reactors or to isolators to be used in such plants (apart the Japanese standard cited in § 2.1, that, unfortunately, is available in Japanese, only).
The lack of existing specific standards is one of the most important problems in the application of seismic isolation to nuclear plants, especially for what concerns the qualification of the isolators. New guidelines and/or recommendations shall be issued to regulate the qualification of these very critical components, maybe starting from the existing ones.

5.1 European Norm 15129 “Anti-seismic devices”

EN15129 is now mandatory (August 2011) in all European countries for any kind of application where seismic isolators are used. However, it is not specifically addressed to nuclear plant. Thus, EN15129 can be used as a sort of minimum requirement in nuclear applications and improvements shall be done. To this aim, some activities are already in progress. The first author of this paper coordinates a similar activities in the framework of the SILER Project (see Forni et al,. 2012) and also in the task 3.2.4 (*Design measures for consequence mitigation of seismic loads*) of the Collaborative Project for the European Sodium Fast Reactor. These activities showed that EN15129 is basically suitable for applications in nuclear plants, with some (not only minor) improvements, which are briefly discussed in the following sections.

5.1.1 Maximum design shear strain of elastomeric isolators

Starting from the first applications of seismic isolation until the end of the ‘90s, a sort of non written rule suggested to design the rubber isolators in order to have a 100% shear strain at the design displacement (this means that the total height of the rubber was equal to the design displacement). In the meanwhile, the experimental tests showed that the isolator failure occurred in the range 300% - 500% shear strain, depending on the hardness and the equivalent viscous damping of the rubber compound (see also §§ 3.1 – 3.2). For this reason, the first written standards allowed the use of higher values for the maximum rubber shear strain at the design earthquake (for example, EN15129 allows a maximum shear strain equal to 250%). A safety factor of 1.2 is required for the total maximum deformation, but no failure tests are required for the qualification of the isolators.
This approach can be accepted for a civil building, but not for a nuclear plant. For beyond design earthquakes, a civil structure is substantially abandoned to its fate (and to its unknown ductility reserve). On the contrary, a nuclear plant must keep the integrity of the most critical components even for extremely violent earthquakes, to avoid any releasing of radioactivity. Seismic isolators are very critical components, thus significant safety factors (3-4, at least) must be assumed against their failure. Moreover, their failure limit must be measured by means of suitable experimental tests (see § 5.1.2).
For the abovementioned reasons, it is strongly recommended to keep the rubber shear strain of the elastomeric isolators lower than 100% at SSE. By the way, the stiffness of the rubber depends on the deformation with a quite non linear behaviour. At low deformations the stiffness is even 2-3 times higher than the value measured at 75% - 125% shear strain. At higher deformation the stiffness increases again, up to 1.5 - 2 times the corresponding value at 100%. Thus, if the design shear strain is equal to 100%, the stiffness of the isolator assumes the minimum value and turns out to be practically constant in a quite wide range (± 25%). It is worth noting that the increment of the rubber stiffness at low deformations helps the isolated building to stay stable under the action of winds or minor earthquakes, while the increment at high deformations reduces the displacement of the isolated building in case of beyond design earthquakes.

5.1.2 Qualification of elastomeric isolators (“type tests”)

The seismic isolators of a nuclear plant are often much larger than those of civil applications, due to the huge masses to isolate. In case of large isolators, EN15129 allows to perform the type tests on scaled models (up to half scale, with diameter/edge no lower than 500 mm). This is substantially due

to the difficulty to test so large isolators and to the non availability of suitable test equipments. For the same reason, it is allowed to apply the seismic load in one horizontal direction only (under the vertical static design load).
As mentioned in § 3.1, rubber bearings are composed by alternate rubber layers and steel plates assembled inside suitable moulds at high temperatures and pressures for quite long time (several hours, depending on the isolator size and the rubber compound). During this phase two critical processes occur: the rubber vulcanization (that transforms the rubber from plastic to hyperelastic) and the bonding between the rubber layers and the steel plates. The latter is given by the chemical reaction of two components, the first previously sprayed on the steel plates, and the second mixed within the rubber compound. For a complete vulcanization and bonding, the temperature must be uniformly distributed inside the whole isolator. Since the rubber is a poor heat conductor, it is quite difficult to guarantee a uniform temperature distribution within large isolators. Thus, for large isolators there is a higher probability to have manufacturing defects, with respect to the smaller ones. For this reason, it is strongly recommended to perform the type tests for the qualification of the rubber isolators of a nuclear plant on full scale prototypes.
The mechanical characteristics of a rubber isolator (stiffness and damping) are mainly displacement-dependent (hysteretic behaviour). However, some velocity-dependent effects are present and can have important effects in extreme conditions, as for example, close to failure. Thus, to correctly evaluate the failure limit of a rubber isolator, it is strongly recommended to test it in real dynamic conditions, with the simultaneous application of all the three components of the seismic load.
At present, there are only two facilities in the world suitable to test large full scale isolators under three-directional dynamic excitations: the first is in California, at the University of San Diego, while the second is in Taiwan. It is worth noting that the type tests are to be performed on a very limited number of prototypes (ranging from 4 to 8). Thus, the corresponding cost has a very limited impact on the total cost of the isolation of a nuclear plant.

4.1.3 Acceptance of elastomeric isolators ("factory tests")
Aim of the factory production control tests is to check that the mechanical characteristic of the produced isolators are the same (within a given tolerance) than those measured on the prototypes during the type tests. EN15129 requires that 20% of the isolators, randomly chosen among the whole production, are subjected to the factory tests. Of course the factory tests are not destructive; they consist in the measure of the effective horizontal stiffness and the vertical stiffness at the design values. The isolator is accepted if the horizontal and vertical stiffness are within ± 20% and ± 30%, respectively, of the value measured in the type tests.
It is worth noting that 20% of the total could be a quite important number of isolators in a nuclear plant and somebody already asked that this number is reduced for nuclear applications. The authors strongly recommend not to reduce the number of isolators to be subjected to the factory tests. A so critical component for the safety a nuclear plant cannot be subjected to control procedures less severe that those applied for the same kind of isolators addressed to civil applications! On the contrary, it is strongly recommended to subject all the isolators to the factory test for the control of the vertical stiffness, at least. In addition, a slight reduction of the tolerances (for example ± 15% and ± 20% for the horizontal and vertical stiffness, respectively) should be advisable.

6. INSPECTION, MAINTENANCE AND REPLACEMENT OF ISOLATORS

6.1. In-Service inspection

The seismic isolators shall be accessible for inspection and maintenance. In civil applications, the room where the isolators are installed is usually reachable from the bottom of the building. In a nuclear plant, for safety reasons, it is not advisable to create an opening in the base raft. Thus, a lateral access must be designed. In case of partially embedded building, the access must be provided with a lift for the movements of the isolators in case of their replacement. For in-service inspection, reference could be made to the abovementioned EN15129.

6.2. Maintenance

The most promising isolators to be used in NPPs are the HDRBs or LRBs (see §§ 3.1 and 3.2). These devices don't require any special maintenance, but particular attention shall be paid to possible corrosion of the anchor system (steel plates and bolts). The room where the isolators are installed in a nuclear plant, especially in case of partial embedment, is better protected from weather effects, vandalism and intrusions of wild animals than the corresponding applications to civil buildings or bridges. No significant variations of temperature are expected between winter and summer. The risk of fire is associated only to the crash plane and can be avoided through suitable joint protections (§ 4.1).
The level of radioactivity below the base raft should be negligible (as far as the author knows, no information about the behaviour of the rubber in radioactive environment is available, yet). Anyway, it should be advisable to keep some isolator prototypes (not loaded) exactly below the reactor, where radioactivity is supposed to be highest, and periodically (say every 5 years) repeat on them the type tests. This should also allow to check the variation of the isolator mechanical characteristics (stiffness and damping) due to the natural ageing. It is worth noting that a similar procedure is in progress since 20 year on 9 isolators of the TELECOM Italia Centre of Ancona, one of the first and most important application of seismic isolation in Italy. After 19 years, these isolators showed a 10% increment in the horizontal stiffness and a very limited decreasing (1%) in the equivalent viscous damping. These values are well within the initially expected variations (and within those allowed by EN15129).

6.3 Replacement

The service life of HDRBs and LRBs is 50 years (or even more). Thus, in normal condition, there is no need to replace them during the life of the plant. In spite of this, the replacement of the isolator must be foreseen in the design, as it could be necessary if some defect (like rubber bulging) is detected during the in-service inspections or after a severe earthquake. However, if the isolator is designed to have a deformation lower than 100% at the design displacement (as recommended in § 5.1.1), the replacement could be unnecessary even after a SSE.
In civil buildings, isolator replacement has already been done several times. The deformability of the superstructure helps the removal of the old isolator and the insertion of the new one with the use of hydraulic jacks.
The more easy way to remove the isolator is to use a destructive technique consisting, for example, in cutting away some rubber layers. However, it is often necessary to remove the whole isolator, for example to subject it to experimental tests (this could be particularly important in the case of a nuclear plant). Other peculiarities of the nuclear plants are the large sizes of the isolator (that require special equipments and room enough around for its movement), and the very high stiffness of the base raft, that can be considered undeformable. Thus, the replacement of the isolators in a nuclear plants requires a particular attention.

7. COSTS

There are very few information about the costs of seismic isolation for NPPs, due to absence of recent applications.
For the JHR, the only application now in progress, the authors were informed by the manufacturer of the isolation system that the cost related to the base isolation was 6 M€.
For IRIS, a preliminary analysis indicated a total cost of 10 M€, approximately. Most of the cost is related to the additional concrete structures to be built to disconnect the building from the ground: one additional foundation layer, a lateral soil containment wall for the embedded part of the plant and the columns supporting the isolators (for a total amount of 10,000 ÷ 12,000 m^3, approximately, depending on the soil conditions and seismicity of the construction site).
Of course, JHR and IRIS are small/medium reactors. For larger reactors like AP1000 or EPR, costs are significantly higher. For example, the isolation of the whole "nuclear island" of EPR should require 500 ÷ 700 large isolators (whose cost ranges between 20 ÷ 30 k€ each) and a very high amount of additional concrete (15,000 ÷ 20,000 m^3, approximately). Other costs are due to the additional

excavation works, and the joints between isolated and not isolated parts of the plants. The cost related to the adoption of the seismic isolation for such plants should be 1% of the total cost, approximately. However, the adoption of seismic isolation allows significant economical savings, especially in the design and development phase, thanks the possibility to standardize the design. In fact, all the components and equipments are subjected to the same horizontal accelerations, independently of the position into the building and the construction site. Finally, significant savings could come from the operability of the reactor, since the possibility to have the plant out of service for long periods due to seismic attacks is significantly reduced.

8. CONCLUSIONS

This paper reported the state-of-the-art of the application of seismic isolation to NPPs, illustrated the most diffused typologies of isolators and interface components and described the related standards and guidelines. Based on the above considerations, the following main conclusions can be done:

- All the present applications or recent new designs of isolated NPPs use rubber isolators (with or without internal lead plugs) acting in the horizontal directions only.
- The isolation in the vertical direction of the whole nuclear island is not possible, yet; at present, if necessary, it shall be limited to some critical components and equipments through suitable energy dissipaters (spring-dashpot devices).
- The technology for cover seismic gap and for pipe expansion joints connecting the isolated part of the plant with the conventionally founded one, is already available.
- The adoption of an horizontal fail-safe system is strongly recommended, to avoid the isolator failure or instability even in case of extremely violent earthquakes (beyond design).
- EN15129 can be used as reference standard for the design, qualification, in-service inspection, maintenance and replacement of isolators. However, since this standard is not specifically addressed to NPPs, EN15129 shall be used as a sort of "minimum requirement" and some improvements shall be hopefully done. In particular it is recommended:

    a) To design the isolator in order to have a rubber shear strain at the SSE lower than 100%. In this way the isolators will have the minimum stiffness at SSE and will have large safety margins in case of beyond design earthquakes.

    b) To perform the type tests on full scale isolators and to test them with real three-directional dynamic excitations.

    c) To perform the factory tests on the whole isolator production (concerning the vertical load capacity, at least).

In conclusion, base isolation is a very promising technique to protect nuclear plants from seismic excitations, but requires further research and development activities, with particular regards to the effects of the vertical acceleration and the beyond design earthquakes.

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