



SEISMIC ISOLATION OF NUCLEAR STRUCTURES – OVERVIEW OF THE FRENCH PRACTICE AND EXPERIENCE

Nadim Moussallam¹, Frédéric Allain², Ilie Petre-Lazar², Micaël Conneson³, Sébastien Diaz³,
Thaihoa Vu⁴, Simon Bouteleux⁴, Benjamin Soupel⁴, Pierre Labbé⁵, Jean-Michel Thiry⁶

¹ Engineer, AREVA Engineering & Projects, Lyon (France) - nadim.moussallam@areva.com

² Engineer, EDF Nuclear Engineering Division, Lyon (France)

³ Engineer, NUVIA Travaux Speciaux, New build Department, Lyon (France)

⁴ Engineer, AREVA Engineering & Projects, La Hague (France)

⁵ Senior Expert, EDF, Nuclear Engineering Division, Saint Denis (France)

⁶ Senior Expert, AREVA Engineering & Projects, Lyon (France)

ABSTRACT

The present paper gives an overview of the best practices and the experience of the French industry, gained over the last 30 years, to implement seismic base isolation systems under nuclear facilities. It contains (a) a brief description of isolated nuclear facilities in France, (b) a point on the specific safety requirements attached to the isolation system, (c) an overview of the analysis methods for the design of the isolation system itself and the supported structures systems and components (SSC) and (c) a presentation of the technical solutions retained for the isolators.

INTRODUCTION

Since the recent seismic events in Japan, and especially the one affecting the Kashiwazaki-Kariwa plant in 2007, there is a global renewal of interest for seismic isolation. The field of application of this technology is often thought to be reduced to high seismicity sites whereas significant advantage could also be expected on moderate seismicity sites. France is a unique example of such moderate seismicity area where seismic isolation technologies have been used by nuclear operators (EDF, AREVA, CEA, ITER Organization) for nuclear facilities, including several power plants, experimental reactors, laboratories, enrichment facilities and spent fuel pools. The use of seismic isolation has been sometimes driven by cost reduction in the design, sometime by standardization purpose and sometimes by investment protection. Nowadays, benefit can also be taken from these systems for the demonstration of the robustness of installations to Beyond Design Earthquake (BDE).

The isolation technology used in France, since the late 70s, is polychloroprene laminated rubber bearings, which would today be referred to as low damping rubber bearings (LDRB). The quality of manufacturing, the management of the qualification process, the tolerances of construction and the knowledge of the material behavior over time have evolved since the first use of this technology. The concept and the material composition itself have essentially been kept constant.

The present paper gives an overview of the best practices and the experience of the French industry, gained over the last 30 years, to implement seismic base isolation systems under nuclear facilities. It contains a brief description of isolated nuclear facilities in France, a point on the specific safety requirements attached to the isolation system, an overview of the analysis methods for the design of the isolation system itself and the supported structures systems and components (SSC) and a presentation of the technical solutions retained for the isolators.

A more detailed synthesis is also being prepared by the authors of the present paper to support IAEA in its effort to issue guidelines on seismic isolation systems for nuclear facilities. This synthesis will be available in AFCEN (2013).

SEISMIC ISOLATION IN FRANCE - PRACTICAL EXAMPLES OF ISOLATED FACILITIES

Seismic base isolation systems, for nuclear power plants and facilities, are aimed at decreasing the dynamic loads on SSC by either (a) filtering the seismic excitation by the insertion of soft devices below the isolated structure, (b) decreasing the response amplitude of the isolated structure by addition of damping, or (c) cutting off the acceleration excitation amplitude by allowing free displacement of structures above a given threshold. In France, given the moderate seismicity of the sites where nuclear structures are located, filtering the seismic excitation was found to provide an adequate answer to the design challenges, without the use of additional damping or cutting off systems.

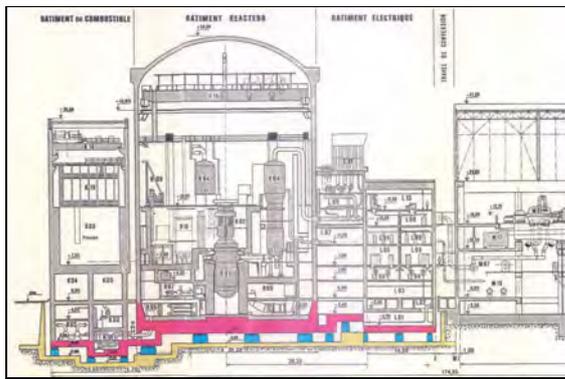
Different types of isolators can be found in the civil engineering industry, depending on the ability of the bearings to transmit shear and/or traction. However, all the existing seismically isolated nuclear structures in France are based upon the same isolation system, transmitting shear loads and compression but not tension forces. The bearings are constituted of alternate layers of polychloroprene rubber (CR) and metallic sheets.

This type of bearings was invented by Eugène Freyssinet in 1952. Since then, countless bridges have been built supported by elastomeric bearings. These structures are constantly subjected to environmental attacks, thermal variations and loads variations. This technology of bearings had therefore been widely challenged over several decades and was logically selected to seismically isolate the Cruas NPP in the late 70s, see Figure 1. La-Hague fuel reprocessing plant followed then with the isolation of its fuel storage pools. Nowadays, all nuclear projects built on seismic isolation do integrate the feedback from Cruas and La-Hague projects to design their own isolation system.

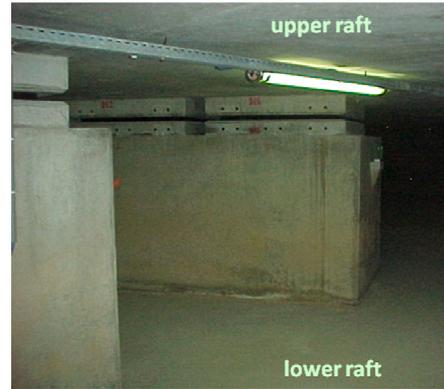
Table 1 gives an overview of the major nuclear projects built on seismic base isolation systems in France. It can be seen from this table that the size of the isolators has been gradually increased over time, whereas the isolation frequency tends to decrease. This reflects the improvements made in the manufacturing process and in the control of the in-core mechanical characteristics of the isolators. For all projects, laminated polychloroprene rubber bearings were selected as the isolator technology. The dynamic behavior of the polychloroprene isolator is quasi-linear when subjected to an earthquake loading. Its equivalent damping is around 6 %.

Table 1: Synthetic description of isolated nuclear facilities in France

Facility	Begining of operation	PGA	Design isolation frequency	Isolators size	Shape factor	Dynamic shear modulus
Cruas-Meysse NPP 4 x 900MWe PWR units	1984	0.3 g	1 Hz	500 x 500 x 66.5 mm square bearing	9.26	1.1 MPa
LaHague Spent Fuel Pools	1985	0.2 g	0.85 Hz	700 x 700 x 147 mm square bearing	17.5	1.1 MPa
Georges Besse II Enrichment Facility	2010	0.3 g	NC	cylindrical bearings d=500 mm h=400 mm	NC	0.7 MPa
Jules Horowitz Research Reactor (JHR)	In construction	0.32 g	0.6 Hz	900 x 900 x 181 mm square bearing	11.25	1.1 MPa
International Thermonuclear Experimental Reactor (ITER)	In construction	0.32 g	0.55 Hz	900 x 900 x 181 mm square bearing	11.25	1.1 MPa

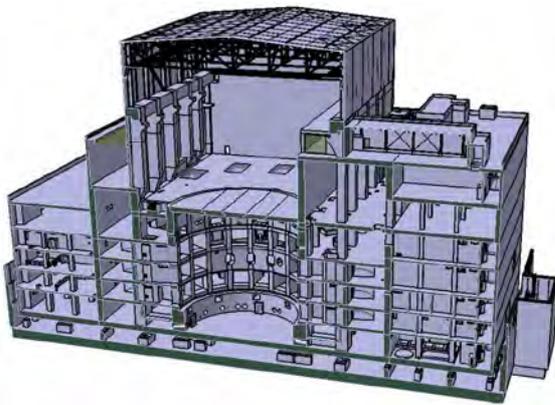


(a)



(b)

Figure 1. Cruas NPP (a) Global cut view (b) Seismic base isolation system – Courtesy EDF

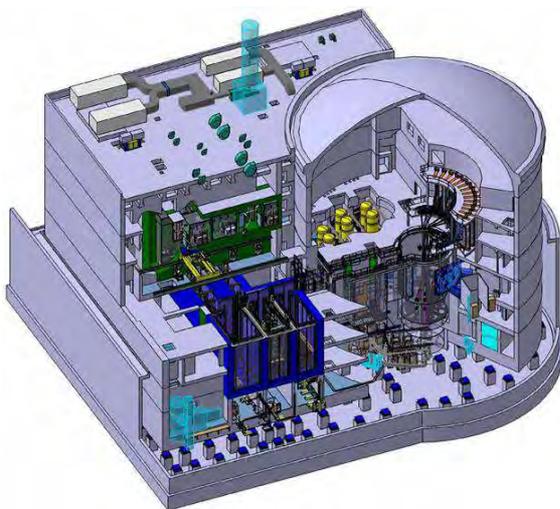


(a)



(b)

Figure 2. ITER (a) Global cut view (b) Seismic base isolation system – Courtesy ITER Organization



(a)



(b)

Figure 3. Jules Horowitz Reactor (a) Global cut view (b) Seismic base isolation system – Courtesy CEA

SAFETY REQUIREMENTS

Implementing a seismic isolation system on a nuclear structure adds a new system to the installation which Safety must be demonstrated in all design conditions. This system supports the whole structure and determines its seismic response. All Safety requirements applying to a non-isolated nuclear facility are equally applicable to an isolated facility. Their fulfillment is generally greatly simplified by the use of a seismic isolation system. Some additional requirements are specific to seismically isolated structures. These include: (a) prevention of the seismic isolation system failure modes, (b) management of the ageing of the isolators characteristics and (c) control and replaceability of the isolators.

Prevention of the seismic isolation system failure modes

A particular attention is paid to prevent the possible failure modes of the isolation system itself. These include:

(a) Excessive shear deformation of the isolators due to the horizontal seismic load. The failure occurs when the shear forces between the rubber layers becomes too high, ultimately leading to a delamination. It is generally observed for a distortion (ratio of the horizontal displacement to the total rubber thickness) higher than 350% for the CR bearing used in France, refer to Kawamura et al (1988) and Mizukoshi et al (1992). This failure mode is prevented by taking sufficient margin to the rupture at the design stage.

(b) Buckling of the bearing under combined vertical and horizontal seismic loads. This failure mode is unlikely because the thickness of the bearings is generally low compared to its other dimensions. Such shape factor is necessary for carrying the weight of usual nuclear structures.

(c) Excessive tension of the isolators due to seismic loads. The vertical seismic loading cumulated with the rocking effect due to the horizontal seismic loading can decrease the compression within the bearing. This can generate a global tension in some of the peripheral bearings, potentially leading to rubber failure. Even though rubber bearings do have some capacity to accommodate tension loads, this capacity has never been credited in the design of isolated structure and margins were taken relative to the risk of tension within a bearing. As a design option, such failure mode can also be avoided by allowing uplift between the upper basemat and the isolators.

(d) Loss of bearing capacity due to fire. This failure mode is prevented by an adequate site protection and by systems that keep potential fire sources outside the open space below the super-structure. Moreover, the rubber mixture in itself can be selected for its flame-retardant properties (as CR is).

(e) Loss of bearing capacity of the Pedestal due to excessive loads transmitted by the isolators. This failure is prevented by applying building design codes with sufficient margins and by robust design of the Pedestals.

Management of the ageing characteristics of the isolators

Since the first use of seismic isolation systems for nuclear facilities in France, the question of ageing of the polychloroprene material was raised, see Coladant (1993). Predictions of the ageing were made but these predictions were based on the limited knowledge available at that time. In the civil engineering industry, the polychloroprene bearings were submitted to largely different environmental conditions from the one below a nuclear facility. Moreover, they were replaced when necessary or regularly; so that they did not provide any information about the ageing of polychloroprene after several decades.

As a consequence, it was requested to monitor the ageing of the isolators throughout the lifetime of the nuclear facilities. This monitoring was achieved by placing samples of isolators next to the actual ones, below the super-structure in the same environmental conditions, and by pre-stressing them with the same compressive stress as the one experienced by the actual devices. On a regular basis, some of these

samples have been extracted and tested. These tests showed that the isolators' characteristics were still within an allowable range and that they will remain so until the end of life of the installations. Indeed the only significant variation was found to be an increase of shear modulus of the polychloroprene, which is stabilizing with time, and which was never measured above 40% whatever the conditions and the samples size (that is an 18 % shift in the isolation frequency which may increase the acceleration applied to the facility). A slight decrease of the rubber bearing damping value was also observed, with no significant consequences.

The samples historically used for the monitoring of ageing characteristics were of reduced size compared to the actual isolators, which tends to accelerate the ageing effects. Moreover, the compression may not have been maintained in such an efficient way in the sample as in the actual isolators, which again maximizes ageing effects. Therefore, the tests performed on these samples provide a conservative estimate of the characteristics variations.

Nowadays, accelerated ageing tests do reproduce the stiffening effect and can be compared to an experimental database consisting in all the tests performed on monitoring samples. Monitoring of the ageing characteristics of isolators is still required for new facilities. This monitoring will likely be made on full scale isolators instead of reduced samples as far as dynamic testing capacities of laboratories are available. Finally, a conservative assumption of the stiffening of the isolation device over the lifetime of the facility is used at the design stage. All design analyses are made considering both beginning of life and conservative end of life stiffness of the isolators.

Control and replaceability of the isolators

In the 70s and early 80s, when seismic isolation systems were first implemented for nuclear facilities and power plants in France, such systems were not meant to be replaceable. For the Cruas NPP, it has been a request from the French Safety Authority to demonstrate that such replacement was possible. A replacement operation was carried out on a single pedestal supporting 2 isolators to make this demonstration in the 90s.

Nowadays, it is a Safety requirement that isolators should be replaceable. Dedicated technologies were implemented on the JHR and ITER project to make such replacement easier.

A regular control of the isolators, including their mechanical characteristics, is mandatory and is part of the maintenance plan of the installation.

DESIGN METHODS

Design of the isolators

The isolators and their connections to the structure are designed in such a way that their performances fulfill the Safety requirements, with an adequate degree of reliability. This includes a guarantee of the proper behavior of the isolation system during the life time of the plant, in its mechanical, physical and chemical environment, as well as in accidental conditions. It does also include the prevention of the different failure modes of the system under design accidental load cases and in beyond design accidental conditions (such as BDE). The design must also ensure the ability to perform routine inspection, and, if needed, replacement of the isolators during the service life of the plant.

In addition to the service loads, the isolators shall accommodate creep, concrete slab shrinkage, construction sequence and thermally induced displacements. Design methodology and criteria come from seismic design standards for conventional civil structures such as EN 1998-1:2004 (Eurocode 8: Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings), EN 1998-2:2005 (Eurocode 8: Design of structures for earthquake resistance – Part 2: Bridges), EN 15129:2010 (Anti-Seismic Devices) and EN 1337-3:2005 (Structural bearings, Part 3: Elastomeric bearings).

Additional safety margins (beyond the safety coefficients defined in the standards) or additional criteria (coming from the know-how and the feedback from previous applications) are taken into account for nuclear projects in addition to the standards requirement. A detailed review of the criteria applied for the design the most recent French projects of seismic isolation is given in AFCEN (2013).

During preliminary design stage, the loads on the isolators are sometime estimated from a simplified model of the isolated structure with an infinitely stiff representation of the basemat. Although giving good estimates for the preliminary design, this approach may lead to significant bias in the results. Therefore, at the detailed design stage, the loads shall be determined based on:

(a) A detailed 3D study of the seismic response of the whole structure, in order to address the impact of the coupling between vertical and horizontal responses and local flexibilities of the basemats and the structure.

(b) A complete time-based calculation of the structure, to address the effect of the shrinkage and of the construction sequence on the vertical loads on the isolators.

(c) Consideration of the temporary load case due to the propping of the upper basemat during the replacement of an isolator. Indeed, this temporary step can induce significant modifications of the bending in the reinforced concrete section.

The mechanical characteristics of the isolators considered in the design can be extracted from the qualification process, if this qualification is performed at the early stage of the project. Beginning of life and end of life values are used as bounding conditions for the life time of the plant.

Design of Structures, Systems and Components (SSC)

The design of SSC within a seismically isolated structure is largely similar to the one in any other nuclear structure. The same design codes apply. Since the type of isolation system used in France is Low Damping Rubber Bearings, the structure analysis can be carried out either with a response spectrum analysis or with a linear time history analysis (i.e. modal superposition analysis). The main specificity comes from the necessity to consider beginning of life and end of life values for the mechanical characteristics of the isolation system. The use of a 3D model for the structural analysis is mandatory in order to correctly account for torsion effects.

The generation of in-structure floor response spectra shall be performed with a 3D model as well, with simultaneous excitation in the three spatial directions. Indeed, the in-structure floor response spectrum in one horizontal direction comprises:

(a) An excitation at the frequency of isolation corresponding to the global displacement of the isolated structure. This excitation produces a first peak on the horizontal floor response spectra, which is essentially constant on all floors of the structure.

(b) An excitation at higher frequencies due to the vertical and rocking modes of the structure. These modes are not filtered by the isolation system and result in local horizontal accelerations. This excitation produces one or several peaks on the floor response spectra in a frequency range similar to the one observed on the vertical floor response spectra, see Politopoulos et al (2011) and Moussallam et al (2011).

In the vertical direction, there is no difference in nature between an isolated and a non-isolated structure, even though the presence of a seismic isolation system could modify the vertical response of the isolated structure.

Because of the large displacements induced by the seismic isolation systems, all connections between the isolated part and the rest of the facility must be designed with adequate compensation capabilities. Several technological solutions exist to provide the necessary flexibility. They include gimbals joints for large diameter pipes and loops for small diameter pipes.

TECHNICAL SOLUTIONS AND MATERIAL CONSIDERATIONS

Applicable standards

Some standards concerning isolators, and more specifically laminated rubber bearings, are applicable for bridges and conventional buildings. These standards offer an interesting base for nuclear applications since they have been engendered by many years of practice. Nevertheless, the EN standards, written to harmonize and standardize engineering and supply practice over Europe, do now constitute the reference. CE accreditation for isolators is based, among other criteria, on the Initial Type Testing (ITT) results of the rubber mixture involved in the isolators' design. EN standards give requirements on geometry and mechanical properties of the isolators but also on elastomeric rubber. Once the ITT qualification is passed, the producer can use a CE marking for all the bearings produced with this mixture and on all its projects. The global same approach is kept for nuclear application but adapted to high level quality requirements of Safety Important Components (SIC). It also means that the very detailed specifications of the EN standards may not be strictly followed since these specifications reduce the rubber choice and correspond to a technical compromise which might not be acceptable for SIC.

Reasons for the technological choice of chloroprene rubber

Laminated bearings have been industrially used since the early 50's in the construction of the motorways in Europe to standardize the bridges crossings. In France and Germany, the Polychloroprene Rubber (CR) has been chosen. In some other countries, Natural Rubber (NR) has been used mainly for costs issues or because of very low temperature area (north USA for example) as its glass transition temperature is lower than CR. In the following, the term NR will not refer to pure natural rubber (damping of which is between 2% and 4%) but to regular NR additive-based compound used by the elastomeric bearing industry.

The rubber material compound needs to be chosen in accordance with the specific project requirements (environment, hazard...). Both NR and CR can be used as bearing material but they have different behavior. Generally speaking, NR has a better elongation and lower hardness whereas CR has a higher tensile breaking load and a higher hardness. The Safety-related behaviors which differentiate these two rubbers are:

(a) Fire resistance capacity: Fire resistance capacity of the CR is better than natural rubber NR. Indeed, the CR is flame-retardant (auto-extinguishable) whereas the NR burns by itself. DuPont (2004) provides examples of such rubber compounds.

(b) Ageing resistance: The rubber mechanical properties will change over the time due to ageing. Ageing is a slow process occurring in the peripheral material, mainly due to air and ozone attacks. NR stiffens over time as the rubber molecules continue to cross-over slowly at room temperature. As a result, the effective shear modulus of the bearing increases. The CR is known as a robust type of elastomeric, especially against ozone and air attacks, see SETRA (2000). It stiffens at a slower rate than NR. To a general extent, CR has better mechanical resistance against environment attacks as the reaction of oxidation is slowed down by the molecules of the CR compound, contrary to NR.

(c) Resistance against thermal hazard: Under cold-temperature conditions, the mechanical properties of the NR are more stable than those of the CR (rubber stiffness increases when temperature decreases). It is a common practice to forbid CR beyond -10°C / -20°C . Yakut et al (2000) addresses this issue. For nuclear application, the isolators are protected from weather conditions in the controlled space between the upper and the lower basemats. As a consequence the temperature is very stable.

(d) Resistance against scragging: In the range of distortions and isolation frequencies, no scragging effect (stiffening of the compound under cycling) can be noted on neoprene-based compound. This issue is treated at the qualification stage to fulfill the standard requirements of EN 15129:2010.

(e) Resistance against radiation: Neoprene-based compound (i.e. CR) is known to have a good resistance to radiation, see Lee (1985). The upper basemat casted on the top of the isolator generally provides a thick shield protecting isolators from radiations.

(f) Creep resistance: Creep resistance of rubber bearing has been widely demonstrated on numerous applications; see Hamagushi et al (2009) for instance.

Determination of the mechanical characteristics of the isolators

The shear modulus is measured in both static and dynamic conditions. Full-scale static and dynamic tests are performed to confirm the vertical and rocking characteristics (stiffness and damping). In order to guarantee the required quality of elastomeric rubber, the following tests are performed:

- (a) Effect of shear strain amplitude,
- (b) Effect of frequency,
- (c) Effect of temperature,
- (d) Shear modulus and damping after accelerated ageing,
- (e) Stability of shear properties under repeated cycles,
- (f) Shear bond test,
- (g) Resistance to low temperature crystallization (if any),
- (h) Resistance to slow crack growth.

Focus on ageing

Durability is a key issue of the nuclear projects. The effect of ageing has a major impact on long-term mechanical properties deviations. Temperature, chemical environment (hydrocarbon...), ambient air (ozone and air), radiations are some of the external conditions driving the ageing of the isolators. However, for NPP isolation, air attack is the main parameter causing CR and NR ageing. Isolators are subject to environmental attack through their external surfaces only. The surface exposed should therefore be small compared to the size of the bearing: the first shape factor S (which corresponds to the ratio between the surface of rubber sheet under compression and its free lateral surface) is the relevant parameter to evaluate the robustness of the isolator against oxidation. The oxidation depth is limited to a few centimeters inside the bearings. Indeed oxidation is located in a relatively thin slice around the bearing and most of the isolator remains anaerobic.

The methodology commonly used to model the long-term mechanical properties ageing process is based upon Arrhenius equation (refer to ISO 11346:2004 and appendix F1 of EN 15129:2010). Arrhenius equation is a simple formula to assess the temperature-dependence of the reaction kinetics (the temperature accelerates the chemical oxidation process which shifts the mechanical properties of the rubber). Appropriate tracers need to be used to monitor the evolution: shear modulus (static and dynamic) is commonly used. The more the temperature increases, the shorter the ageing test needs to be for the tracer to reach a given deviation. The experimental process is thus to submit isolators or samples to several duration / temperatures and perform regularly tracer measurement (at ambient temperature). The tracer variations are then plotted versus the duration and post-processed using Arrhenius equation.

The representativeness of the methodology needs to be carefully addressed especially regarding the following issues:

(a) The applicability of the Arrhenius equation shall be demonstrated (correlation of the affine function model and the plotted points). At least three different temperatures shall be used, see Figure 4 and 5 for an example of such demonstration.

(b) The deterioration mechanism shall remain the same in the range of the tested temperatures (range of validity of Arrhenius equation). The risk is that too high temperatures may initiate other damaging mechanisms than the one observed in the normal environment of the isolator – these mechanisms would then pollute the measurements.

(c) The sample size (if any, instead of full-scale isolator) and its external surface exposure need to be realistic. The shape factor and the exposed region need to be in accordance with the full-scale bearing.

Finally, it is recalled that the ageing models should be complemented by a monitoring of the actual ageing of the isolator (see paragraph on safety requirements). Monitoring results can be used to update the ageing model if needed.

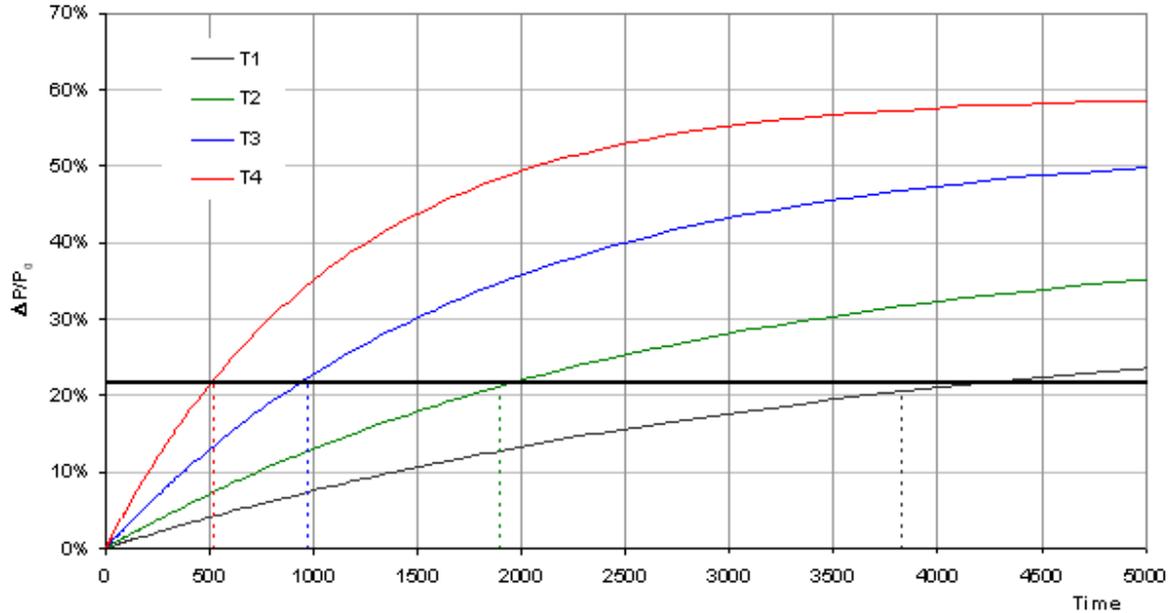


Figure 4. Example of a typical isothermal variation of a tracer versus ageing duration

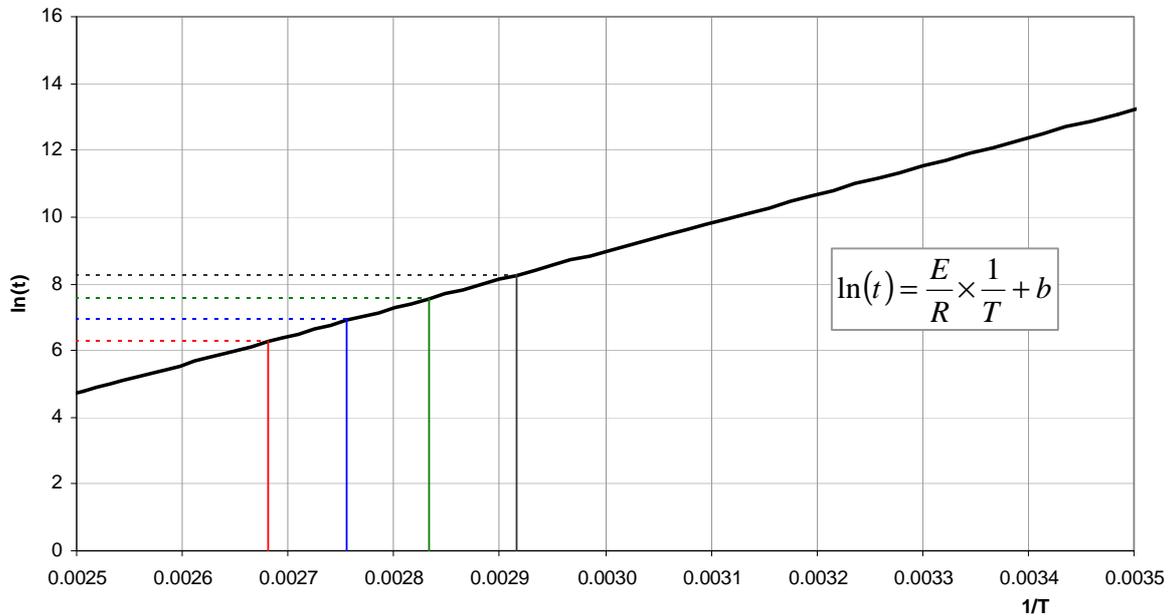


Figure 5. Example of a typical Arrhenius post-processing of the tracer isothermal curves – Affine slope with E , activation energy of the reaction in J/mol and R , Boltzmann constant expressed in units of energy ($R = 8.314 \text{ J/mol.K}$), T the temperature and t the time.

CONCLUSION

After more than 30 years of use of seismic isolation systems for the nuclear industry in France, significant experience has been gained in designing, manufacturing, installing and monitoring these systems. Because of the new international interest expressed for this type of technology, the French industry, from plants owner to isolators manufacturer have joined in a common effort to share this experience with the international community. The present paper is part of this effort. A more complete picture will be given in AFCEN (2013).

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