Regulatory requirements to carry out *Complementary Safety Assessments* and to implement *Hardened Safety Core* provisions in the Light of the Lessons Learned from the Fukushima Daiichi Accident

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Abstract Following the Fukushima Daiichi Accident, ASN has established regulatory requirements for all the Operators to carry out a *Complementary Safety Assessment* for each nuclear facility in line with the European Stress Tests and the French Prime Minister request. It was expected that this process would reevaluate the available safety margins beyond design basis and, identify potential *Cliff-Edge Effects* and *Feared Situations* following an extreme event. Extreme events, such as natural hazards significantly higher than design basis, lead to the loss of heat sink and/or electrical supplies and, affect several nuclear facilities on a same site. Then, regulatory requirements have been introduced to deal with potential unacceptable consequences resulting from these extreme events. The strategy includes two options. The first option is to decrease the level of hazard in the nuclear installations by reducing the amount of nuclear or hazardous substances. The second option is to provide the demonstration to reach a safe state for the nuclear installation following an extreme event. This demonstration should be supported by a set of existing or new provisions withstanding to extreme events with a high level of confidence, the *Hardened Safety Core*. In January 2015, ASN has established in its resolutions the basis of the implementation of the *Hardened Safety Core* for the Research Reactors, the Fuel cycle Facilities and the associated nuclear sites. They set specific requirements for the design of the *Hardened Safety Core* provisions and deadlines for their implementations. To reach a high level of confidence for levels of natural hazards with a very low annual frequency of exceedance is a real challenge. It is not always supported by available data and guidance. In order to comply with deadlines set in the regulatory programme, the stakeholders have assumed uncertainties and defined framework as workshop, to progress on these topics. The experience feedback from this programme would be useful in the context of the development of the Design Extension Conditions and the related safety requirements.

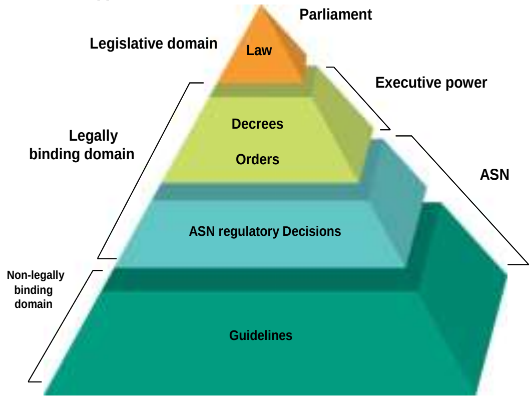
1. Context

The Fukushima accident, triggered by an earthquake and a tsunami on an exceptional scale, confirmed that despite the precautions taken in the design, construction and operation of the nuclear facilities, an accident is always possible. In this context, and given its knowledge of the 150 French nuclear facilities, through its regulation and oversight, ASN considered in the days following the accident that a complementary assessment of the safety (CSA) of the facilities, with regard to the type of events leading to the Fukushima disaster, should be initiated without delay, even if no immediate emergency measures were necessary.

2. *Complementary Safety Assessment* as a regulatory requirement

These *Complementary Safety Assessments* are part of a two-fold approach: on the one hand, performance of a nuclear safety audit on the French civil nuclear facilities in the light of the Fukushima event, which was requested from ASN on 23rd March 2011 by the Prime Minister, pursuant to article 8 of the TSN Act and, on the other, the organization of "stress tests" requested by the European Council at its meeting of 24th and 25th March 2011 [1].
In order to manage the *Complementary Safety Assessments*, ASN issued twelve resolutions on 5th May [2] requiring the various Licensees of the nuclear facilities to perform these CSA in accordance with precise specifications.

[ASN resolutions]: *Pursuant to article 4 of the TSN Act, ASN can take regulatory resolutions to point out decrees and orders issued concerning nuclear safety or radiation protection, which are submitted to the Government for approval. ASN also issues individual resolutions concerning nuclear activities (for example, commissioning authorization for a basic nuclear installation, authorization to use radioactive material transport packaging, authorization to use radioactive sources, definition of requirements concerning the design, construction, operation or decommissioning of a facility, etc.).*
Non-compliance with the ASN resolutions could lead to an offence.



3. Scope of the CSA

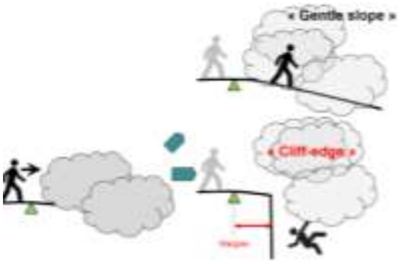
The *Complementary Safety Assessments* concern the robustness of the facilities to extreme situations such as those which led to the Fukushima accident. They complement the permanent safety approach followed.

To ensure consistency between the European and French approaches, the French specifications for the *Complementary Safety Assessments* were drafted on the basis of the European specifications produced by WENRA (Western European Nuclear Regulators' Association) and approved by ENSREG (European Nuclear Safety REgulators Group) on 25th May 2011. The provisions of the French specifications are consistent with those of the European specifications.

The CSA thus consists of a targeted reassessment of the safety margins of the nuclear facilities in the light of the events which took place in Fukushima, that is extreme natural phenomena (earthquake, flooding and a combination of the two) placing considerable strain on the safety functions of the facilities and leading to a severe accident. The assessment first of all concerns the effects of these natural phenomena; it then looks at the loss of one or more systems important for safety involved in Fukushima (electrical power supplies and cooling systems), regardless of the probability or cause of the loss of these functions; finally, it deals with the organization and the management of the severe accidents that could result from these events.

Three main aspects are included in this assessment:

- the steps taken in the design of the facility and its conformity with the design requirements applicable to it ;
- the robustness of the facility beyond the level for which it was designed; the licensee in particular identifies the situations leading to a sudden deterioration of the accident sequences (*Cliff-edge Effects* and presents the measures taken to avoid them) ;
- all possible modifications liable to improve the facility's level of safety.



***[Cliff-edge Effects]:** High discontinuity in the scenario causing notable and irreversible aggravation of the accident (significant increase in releases, significant decrease in time before undesirable situation is reached, etc.).*

ASN decided to apply the *Complementary Safety Assessments* to all French nuclear facilities and not simply to the power reactors. Thus, virtually all of the 150 French nuclear facilities will undergo a *Complementary Safety Assessments*, including for example the EPR reactor currently under construction, or the spent fuel reprocessing plant at La Hague. In this respect, the French specifications have been extended compared to those adopted at the European level by ENSREG.

As of the beginning of the process, the association of stakeholders, particularly HCTISN, asked ASN to place particular emphasis on social, organizational and human factors, especially subcontracting. The Fukushima accident showed that the ability of the Licensees and, as necessary, its subcontractors to organize and work together in the event of a severe accident is a key factor in the management of such a situation. This ability to organize is also a key aspect of accident prevention, facilities maintenance and the quality of their operation. The conditions for the use of subcontracting are also tackled in the French *Complementary Safety Assessments*.

4. A graded plan

The CSA concern virtually all the 150 basic nuclear installations in France (58 nuclear power generating reactors, EPR reactor under construction, research facilities, and fuel cycle plants).

These facilities have been divided into three categories, depending on their vulnerability to the phenomena which caused the Fukushima accident and on the importance and scale of the consequences of any accident affecting them.

The classification in the tree batches takes in account:

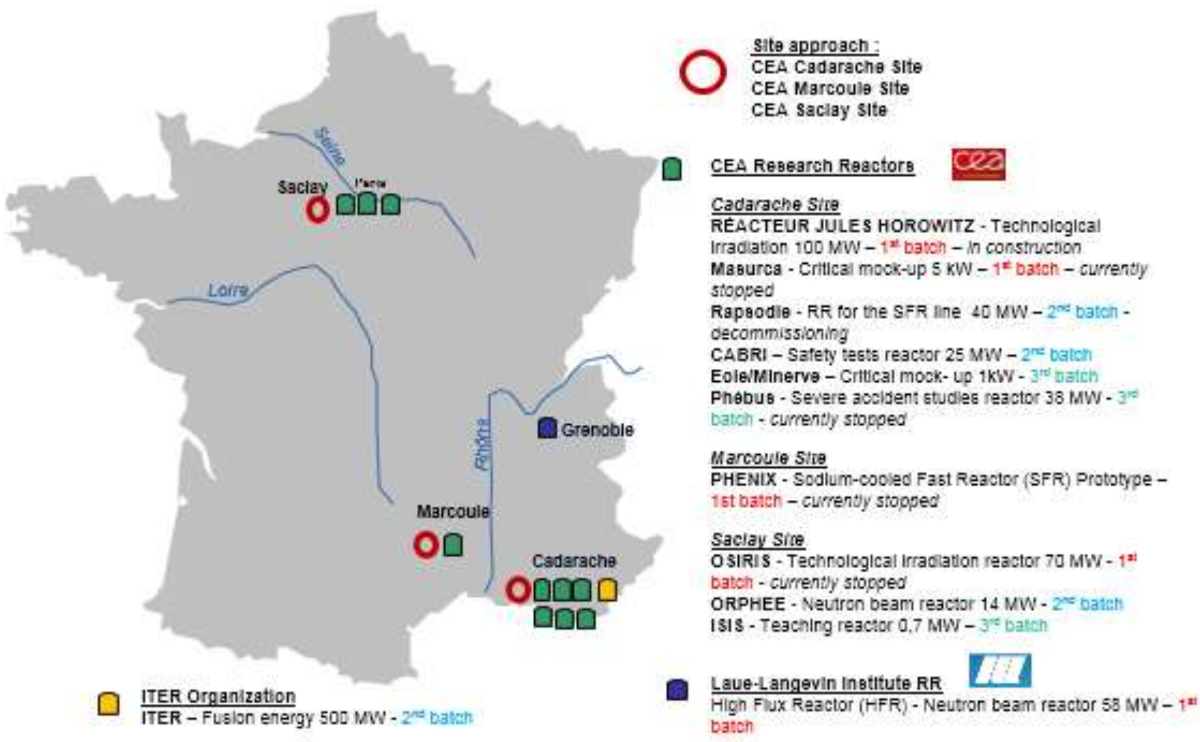
- the type of the facility:
  - nuclear reactors based on the thermal power,
  - fuel cycle facilities based on the annual processing capacity,
  - …
- the amount of radioactive material and hazardous substances,
- the potential off-site releases and the vicinity of the plant,
- the robustness and the independence of the containment barriers.

For the 79 facilities felt to be a priority, first batch, including the 59 power reactors in operation or under construction, the Licensees (AREVA, CEA, EDF, Laue-Langevin Institute) submitted their reports to ASN on 15th September 2011.

For the facilities of lower priority, batch 2, the Licensees are required to submit their reports before 15th September 2012.

Finally, the other facilities, batch 3, will be dealt with through appropriate ASN requests, in particular on the occasion of their next ten-yearly periodic safety review, except for about ten facilities for which decommissioning is nearing completion.

The classification of the French Research Reactors is presented on the map below:



5. CSA as part of the existing safety improvement process

These assessments were carried out in addition to the safety approach performed permanently. The CSA is complementary to existing safety improvement processes:

- Periodic Safety Reviews (PSRs)
- integration of Operating Experience Feedback (OEF).

	Periodic safety review	Complementary Safety Assessment
Regulatory requirement	Required by law: article L 593-18 of the Code of the Environment	Required by ASN resolutions
Periodicity	Every 10 years	Once
Scope	The technical scope is the overall review of the safety cases. It is presented at the Title III "Demonstration of nuclear safety" of the Order of 7 February 2012 setting the general rules relative to basic nuclear installations The main points are: - principle of defense in depth, - a prudent deterministic procedure and shall also include probabilistic analyses of accidents and their consequences, - technical, organizational and human dimensions - 4 safety functions (control of nuclear chain reactions, evacuation of the thermal power produced by the radioactive substances and nuclear reactions, containment of the radioactive substances, protection of persons and the environment against ionising radiation). - list of internal and external hazards to consider	The technical scope is defined in the ASN resolutions (issued in 2011, 2012 and 2015). Initiating events (beyond design basis) to be taken into account : - Earthquake - Flooding - Other extreme natural events The Consequential loss of safety functions to be assessed using a deterministic approach : - Loss of electrical power, including station blackout (diesels, etc.), - Loss of the ultimate heat sink, - Combination of both The severe accident management issues have to be tackled : - Loss of the core cooling function, - Loss of the spent fuel storage pool cooling function,
Main Steps	The PSR Process is organised in 2 steps: • Conformity with design requirements and Compliance with regulations : - Authorization for creation, Site Licence, - Environmental & radiological regulatory, - ASN technical resolutions, - environmental permits for the installation, - ... • Safety Reassessment: - Reassessment considering the current state of art, - Best practices applicable at national and international levels, in nuclear and non-nuclear activities, - Review of methods used in the safety cases, the accident studies, in the evaluation of natural hazards, ... - Improvements and lessons learnt from operating experience,	The CSA process includes: • Safety margins taken in the facilities design basis and plant conformity to its design requirements, - assessment of available design margins, diversity, redundancy, physical separation, ... - assessment of the cliff-edge effects beyond which fundamental safety functions would be lost, • Safety margins taken in the facilities design basis and plant conformity to its design requirements, • Possibility of mobile external means and the conditions of their use, • Possibility of mutual help between units from a same site.

6. Milestones for the post-Fukushima regulatory programme

• March 11 2011	• Fukushima Accident
• March 23 2011	• Declaration of the French Prime minister asking for national audit to be carried out for all French nuclear facilities, in priority for NPPs
• May 5 2011	• ASN Commission adopted 12 resolutions requiring Licensees of French nuclear facilities to conduct a complementary safety assessment (CSA)
• June 1 2011	• French Licensees' CSA methodologies sent to ASN
• July 6 2011	• Advisory expert committee meeting on CSA methodology
• July 19 2011	• ASN Opinion on Licensees' CSA methodology
• Sept. 15 2011	• French Licensees' CSA reports sent successfully to ASN (1st batch)
• Nov 8 2011	• Joint meeting of the French advisory expert committees, based on the French TSO IRSN review of the CSAs
• Dec. 2011	• ASN's report on CSAs
• Janv. 3 2012	• ASN issued its opinion on French CSAs
• June 26 2012	• ASN resolutions: Complement to CSA + proposals for hardened safety core
• June 2012 to July 2013	• French TSO IRSN reviews complements and proposals (1st & 2nd batches)
• April 2013	• Joint Meeting of the French advisory expert committees for 1st batch
• July 2013	• ASN resolutions consisted in enforcement notices to implement the transition measures pending the implementation of the *hardened safety core*.
• July 2013	• Joint Meeting of the French advisory expert committees for 2nd batch
• Jan. 8 2015	• ASN resolutions: Complement to CSA + requirements to define and to design the hardened safety core (1st & 2nd batches)
• 2016 - 2017	• ASN guidance to take into account Fukushima accident in the design of the new nuclear facilities (*in progress*)
• Until 2018-2023	• Long term programme to take in account post-Fukushima feedback actions

7. A consistent approach

Through the following regulatory work, ASN has implemented a common process for all the installations: NPPs, FCFs and RRs, in order to build a consistent approach.

The ASN resolutions and requirements for all the installations have been built from:

- the Licensees' CSA reports which had the same specifications,
- the IRSN assessment findings,
- the French advisory expert committees advices,
- The ASN inspections findings.

ASN has set all the elements which could contribute to increase the robustness of the safety of the facilities. These elements are the basis of the ASN requirements and are of three types.

1/ the requirements that include, first, common provisions to all the installations covered by the CSA. These cover the following topics:

- the enhancements of nuclear standards and guidance,
- the setting of a group of robust materials and organizational provisions for extreme events, , *Hardened Safety Core*, to prevent a serious accident or limit its progression, limiting massive releases and allow the Licensees to carry out the expected actions related to emergency preparedness and response ;
- the arrangements to ensure an operative organization and suitable means to manage events which could affect all or part of the facilities on a same site. These include in particular the need for an emergency control room designed to withstand to extreme natural hazards,
- taking into account the social, organizational and human factors in crisis-management operations, including the definition of human actions required to

manage an extreme event, the list of the expected skills to manage these situations and whether these skills are likely to be held by contractors.

These generic provisions to all nuclear installations were defined as a result of joint work between the relevant ASN departments in charge of the different types of facilities (NPPs, research reactors, fuel cycle facilities ...).

2 / This set of generic requirements is supplemented by the provisions specific to each research reactor taking in account its current life-cycle phase and its design provisions. These could deal with specific materials to withstand an extreme natural event (earthquake, flooding, tornado …) or complementary assessments of the installation's safety cases in the framework of the CSA, as the *Feared Situations*.

8. The post-Fukushima ASN resolutions in details

The first resolutions were taken in May 2011. They defined the scope of the *Complementary Safety Assessments* s in the light of the Fukushima accident. The details are provided above. The deadlines were related to the batches of the installations were fixed in the resolutions. The target dates were September 2011 for most facilities and September 2012 for one of them.

The second resolutions were taken in June 2012 [3]. ASN prescribed the Licensees to establish a *Hardened Safety Core* of robust material and organisational measure in order to prevent or mitigate the progress of a major accident, to mitigate large-scale radioactive releases and to enable the Licensees to perform its emergency management duties in the case of an extreme event. The *Hardened Safety Core* have to be designed or qualified with significant margins beyond design basis and, composed of independent and diversified systems, structures and components. The Licensees shall justify the use of undiversified or existing SSCs.
ASN also required the Licensees to assess some cases *Feared Situations* specific to the installations, interim measures and complementary arrangements to manage emergency situations according to the risks on sites, in particular towards earthquake, flood and chemical risks. Some steps aiming to enhance skills and social and psychological care were also prescribed.

The third resolutions were sent July 2013. They consisted in enforcement notices to implement the interim measures pending the implementation of the *Hardened Safety Core*.

The fourth resolutions were sent in November 2013 [4] and January 2015 [5]. They provide the definition of a *Hardened Safety Core* for each facility and site to manage *Cliff-edge effects*. They specify the list of SSCs composing the *Hardened Safety Core* and their qualification requirements:

- New SSCs designed according to industrial standards,
- Existing SSCs verified according to industrial standards, or verified according to methods allowed during PSRs.

The level of external hazards to consider for the *Hardened Safety Core* have been set. Then, some general and specific requirements were written concerning Systems, Structures and Components design and sizing for the *Hardened Safety Core* as well as additional studies.

Finally, ASN required additional arrangements to manage extreme emergency situations and related to organizational and human factors:

- arrangements to ensure the ability of the *Hardened Safety Core* SSC to work the first 48 hours without any external support and supplies,
- availability in the Emergency Control Room of key parameters related to the safety functions of the facilities (level of water in a pond, T°, …),
- arrangements to provide external support (human resources, additional materials and supplies) to a site affected by an extreme event.

These decisions also define deadlines to implement the *Hardened Safety Core*. The strategy foster an early implementation of these enhancements for the safety. Also, ASN assumed that this strategy could lead to uncertainties regarding the compliance of the Licensees' proposals and the regulatory requirements and, to risks on the programme deliveries.

9. Basis for Review and Assessment

o Process to define the *Hardened Safety Core* provisions

At the installation level, the *Hardened Safety Core* provisions should be defined to limit the radioactive releases or direct irradiation during the first days following an extreme event. These provisions should ensure that the installations still comply with the safety levels or safety objectives set in the related authorizations.

The levels of natural hazards to be considered for an extreme event are discussed below. These situations conduct to the loss of the heat sink and the electrical supply. The robustness of the existing arrangements, safety systems or organizational provisions, in such cases should be demonstrated or they should be considered lost.

Taking in account the availability of the existing provisions following an extreme event, the accident scenarios leading to unacceptable consequences are identified as *Feared Situations*.

Operating strategies should be established to manage the *Feared Situations* and to ensure that the research reactor would reach a controlled state and then a safe state.

All the necessary provisions, existing and additional ones, requested by these safety cases, form the *Hardened Safety Core*.

When it is not possible to demonstrate the prevention and/or the mitigation of the *Feared Situations* taking in account the existing and reasonably practicable additional arrangements, the strategy should lead to reduce the hazard potential as the quantity of nuclear substances.

o The *Hardened Safety Core* provisions for the Research Reactor

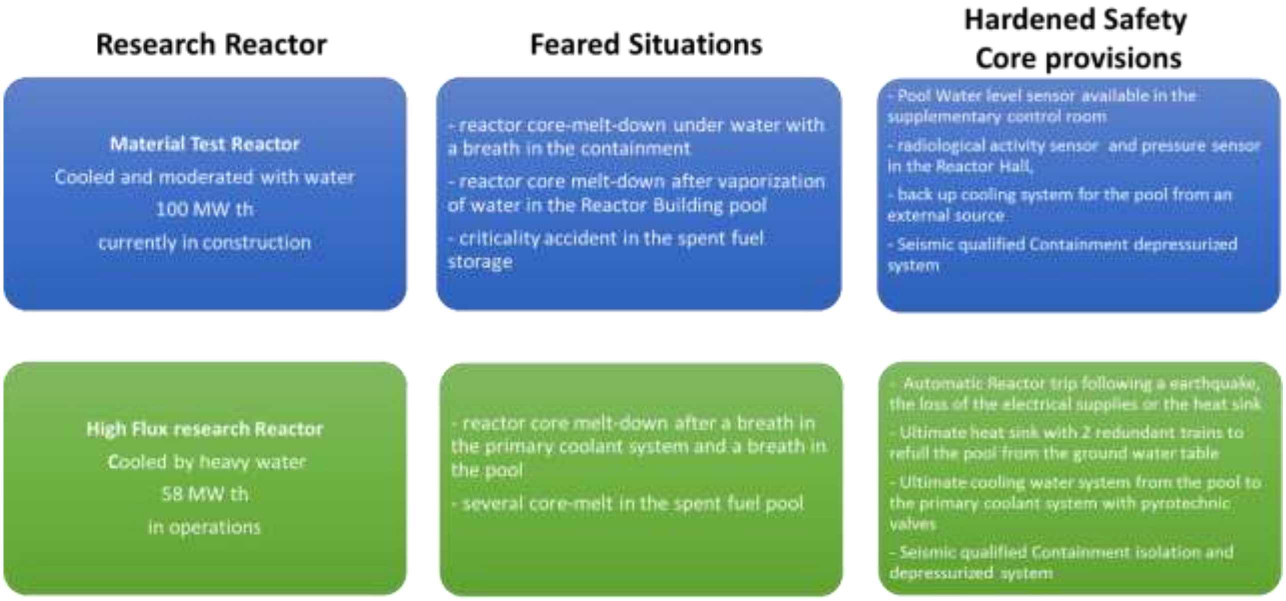
The implementation of the *Hardened Safety Core* provisions seeks to prevent and mitigate a severe accident, to minimize radioactive releases to the public and the environment and, to enable the Operator to carry out its duties in an emergency under conditions generated by an extreme event.

- Technical provisions

For a research reactor, the safety features part of the *Hardened Safety Core*, aim to keep the safety functions operational. And, they encompass:

- provisions to prevent fuel melting by controlling the reactivity then maintaining the removal of heat from the fuel (1st confinement barrier),
- provisions to limit releases in the case of a severe accident and to prevent any degradation of the confinement function as the protection and the isolation of the containment,
- provisions to ensure that the information necessary to manage an emergency would be available as information about important reactor parameters, radiological conditions at the reactor facility and the site and meteorological conditions.

As examples, the following *Feared Situations* have been studies by the Operators and the following additional provisions have been proposed:



In addition, the Research Reactor Operators have also planned to build emergency control room which should withstand to extreme external hazards and taking in account the related conditions following such situations. Key safety parameters of each nuclear installation on the site should be available in the emergency control rooms.

- Human and organizational factors

Regarding the human and organizational provisions, the emergency plan and procedures should take into account extreme natural events which could affect simultaneously several facilities such as research reactor on a nuclear site and conduct to operate in degraded conditions.

To define the *Hardened Safety Core* provisions, particular attention should be paid to the conditions necessary to achieve the expected actions such as:

- sufficient human resources in terms of volume, skills, training and availability,
- a clear definitions of the roles and duties of the different stakeholders,
- information management system reliable and centralized,
- adequate communications means,
- available emergency operating procedures, tools and personal protective equipment,
- facilities withstanding to extreme events and protecting staff from the related conditions,
- safe paths on site to carry out the expected operations,
- sufficient time period to enable operating personnel to initiate the expected actions.

As examples, the CEA has proposed and is currently implementing as part of its Emergency Preparedness and Response arrangements:

- a site approach to prioritize the actions,
- an organization of mutual help between the CEA sites in the case of an extreme event after the first 48 hours. The interfaces between this organization and the local team is detailed in the Emergency plans of the sites. This organization has three level of staffing until more than 35 individuals related to firefighting, rescue teams, radioprotection, environmental monitoring, logistic and medical. It also includes mobile materials and supplies,
- a coordination of this mutual help is supported by the Head quarter in Paris.

- **Extreme natural hazards**

  - **Seismic hazard**

The methodology to define the seismic hazard level in the design basis of the French nuclear facilities is presented in a Fundamental safety rule n°2001-01 [6]. A deterministic approach is applied and, as far as practicable, probabilistic methods taking into account the current state of science and technology.

The first step of this methodology is to identify and define the maximal historical probable earthquakes (*Séismes Maximaux Historiquement Vraisemblables - SMHV*) for the nuclear site which should be considered as the most penalizing events with highest intensity over the past thousand years. Then, the Design Basis Earthquake (DBE) spectrum (peak ground acceleration) is built by calculating the magnitude of the DBE from the *SMHV* Magnitude, plus 0,5.

For an extreme situation, ASN fixed the level of the seismic hazard as the spectrum resulting of the maximum of [1,5 * DBE ; Probabilistic Seismic Hazard Analysis with 20 000 return period] taking in account potential site specific effects. The site effects are related to the geology (soil properties, sediments, rock …), seismic soil behavior (liquefaction) and geometry (topography, basin …).

For the Research Reactors sites, the deterministic part of the "Extreme Earthquake" was higher with a significant margins than the spectrum resulting from a probabilistic method. It has made easier the review and assessment of this topic as a lot of work has already been carried out by the experts from the Operators and the technical support officer on the DBE.

ASN recognized that the use of the PSHA in the French context is not ready yet; modelling work is needed.

- **Tornado**

Tornado has been one of the natural hazards set in the ASN resolutions of 8 January 2015 [5]. However, no guidance for the nuclear installations is available to deal with the tornado hazards for the design basis and extreme situations.

So, ASN proposed to the Operators to use American guides [7 & 8] as it is the current state of the art and the best practices.

The works carried out by the French Operators EDF (NPPs), AREVA (FCFs) and CEA (RRs) were reviewed and assessed in a same regulatory intervention in 2016. They used the tornado databases from national experts as KERAUNOS who has mapped nearly 800 events since the 12th century with 90 level EF3 events on the Fujita scale, 15 level EF4 events and 2 levels EF5. They applied a probabilistic approach based on the rate of the area affected by tornados and the area of the region studied. The tornado phenomena and its effects on the facilities are modelled following the American guides [7 & 8].

The Research Reactor Operators selected:

- for design basis, a reference tornado EF1 (Fujita scale) with a speed of 45 m/s and a pressure drop of 1,27 kPa corresponding to an annual frequency of exceedance of 10^{-5},
- for extreme situations, a reference tornado EF3 with a speed of 65 m/s and a pressure drop of 2,65 kPa corresponding to an annual frequency of exceedance of 10^{-6}.

This level for the design basis complies with the WENRA reference level for the existing reactors [9] T4.2 which sets a target value of an annual frequency of exceedance of 10^{-4}.

This level for the extreme situations is consistent with the target value aimed by ASN for the extreme natural hazard. However, the French regulation[1] requires that the nuclear safety is demonstrated by a prudent deterministic procedure. And, a statistical methodology in the French context with a limited number of events, needs to be completed. So, ASN has recommended to go on the works on this topic by developing a local study approach and analyzing criteria which could affect the frequency, the magnitude of tornadoes and its effects.

10. Conclusions and Perspectives

The concept of the *Complementary Safety Assessment* and the *Hardened Safety Core* have been introduced in the French regulations respectively in 2011 and 2013. The aim was to complete the safety demonstration and to cover extreme situations which could affect several nuclear facilities on a same site taking in account potential isolation of the site.

[1] Article 3.2 - Order of 7 February 2012

Since, the concept of Design Extension Conditions (DEC) has been introduced in the IAEA safety requirements[2] and the WENRA Safety Reference Levels for Existing Reactors. ASN has also issued in November 2015 a resolution [10] dealing with the content of the Safety Report of a nuclear installation. Regarding the application of the defense in depth, it is established that it should be demonstrated in the safety report, sufficient safety margins to prevent any *Cliff-edge Effect* in the nuclear installation.

The Post-Fukushima enhancements programme has started at an early stage to deal with topics related to DEC. This programme has already led to implement major modifications on Research Reactors and the nuclear sites. The feedback of this programme would be useful to face challenges as the definition of natural hazards of an extreme event with a low level of uncertainty and the associated methodologies and, the provisions for the design, the construction and the operations of the items important to safety which have to withstand to extreme events.

11. References

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[2] IAEA guide SSR-3 - Safety of Research Reactor - 2016