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Science of nuclear safety post-Fukushima

Continuously improving safety of nuclear installations: An approach to be reinforced after the Fukushima accident

La sécurité des installations nucléaires et son amélioration : Les mesures à prendre après l'accident de Fukushima

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ABSTRACT

After the Three Mile Island accident in 1979 and the Chernobyl accident in 1986, the Fukushima accident shows that the probability of a core meltdown accident in an LWR (Light Water Reactor) has been largely underestimated. The consequences of such an accident are unacceptable: except in the case of TMI2 (Three Mile Island 2) large areas around the damaged plants are contaminated for decades and populations have to be relocated for long periods. This article presents the French approach which consists in improving continuously the safety of the Nuclear Power Plants (NPP) on the basis of lessons learned from operating experience and from the progress in R&D (Research and Development). It details the key role played by IRSN (*Institut de radioprotection et de sûreté nucléaire*), the French TSO (Technical and scientific Safety Organization), and shows how the Fukushima accident contributes to this approach in improving NPP robustness. It concludes on the necessity to keep on networking TSOs, to share knowledge as well as R&D resources, with the ultimate goal of enhancing and harmonizing nuclear safety worldwide.

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RÉSUMÉ

Après l'accident de Three Mile Island en 1979 et celui de Tchernobyl en 1986, l'accident de Fukushima montre que la probabilité d'une fonte du cœur dans un réacteur à eau légère a été considérablement sous-estimée. Les conséquences d'un tel accident sont inacceptables : à Tchernobyl comme à Fukushima de vastes zones autour des centrales endommagées sont contaminées pour des dizaines d'années et les populations ont été évacuées pour de longues périodes. Le présent article présente le programme français qui consiste en une amélioration continuelle de la sûreté des centrales nucléaires en tirant les leçons de l'expérience acquise et des progrès en Recherche et Développement (R&D). On insiste sur le rôle essentiel joué par l'Institut de radioprotection et de sûreté nucléaire et on montre comment l'accident de Fukushima contribue à améliorer le fiabilité des centrales. On conclut par la nécessité pour les Organisations de sécurité nucléaire de collaborer et de partager les connaissances ainsi que les ressources en R&D, avec le but ultime d'améliorer et d'harmoniser la sûreté nucléaire à travers le monde.

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1. Introduction

After the Three Mile Island accident in 1979 and the Chernobyl accident in 1986, the Fukushima accident, which affected 3 BWR units, shows that the probability of a core meltdown accident in an LWR has been largely underestimated. The consequences of such an accident are unacceptable: except in the case of TMI2, large areas around the damaged plants have been contaminated for decades and populations have had to be relocated for long periods. The economic costs, direct as well as indirect, are very high for society. Therefore, it is required that the highest level of safety and security be maintained at all times in each country concerned.

In France, where more than 75% of electricity is produced by NPPs, the TSN (Transparency and Security in the Nuclear field) act of June 2006 has institutionalized the French nuclear safety and radiation protection framework. This article will describe first the French organization for nuclear safety, the particular role of the IRSN in this organization, and the main safety improvements already in place in the nuclear facilities or in progress. It will then present the safety objectives set up for Generation III plants to be built in France, the IRSN position in the perspective of long-term operation of French Generation II plants, and the recent impact of the Fukushima accident. Finally, it reviews the ongoing international networking of the Technical and scientific Safety Organizations (TSOs), which should contribute to enhance nuclear safety and harmonize safety analysis practices, worldwide.

2. The nuclear safety approach in France

2.1. The institutional framework

The maturation of the French organization in nuclear safety and radiation protection has progressively resulted in an institutional framework, which has been consolidated by the TSN act. It is made of 4 distinct poles:

– the operators, responsible for the safety and security of their installations;
– the regulatory bodies (the French "*Autorité de sûreté de nucléaire*" or ASN for the nuclear safety and radiation protection), defining and enforcing regulation;
– the "civil society" (Local Committees for Information, High Committee for Transparency and Information on Nuclear Safety), concerned with the societal vigilance;
– the public scientific and technical expertise on nuclear and radiological risks, provided by the French "Institut de radioprotection et de sûreté nucléaire" (IRSN).

The quality of the dialogs among these 4 poles, each of them having in its own role with its own judgment, contributes to the efficiency of this system.

It is important to note that the TSN act has institutionalized an important aspect of the nuclear safety approach, by imposing Periodic Safety Review (PSR) of each French nuclear installation, typically every ten years or less if judged necessary. The objectives are twofold: (1) check that the facility still complies with the safety reference set up at the time of last licensing and (2) upgrade the safety reference on the basis of lessons learned, operating experience and progresses in scientific knowledge and technology.

2.2. The role of IRSN in enhancing nuclear safety

IRSN is a public body created in 2001 under the supervision of 5 ministries: Environment, Industry, Health, Research and Defense. It is the public expert in research and assessment regarding nuclear and radiological risks. It contributes to defining public policies for nuclear safety and security, for human and environmental protection against ionizing radiations, and for protection of nuclear material, installations and transportations against malicious acts. In case of emergency, it gives advise to the authorities and coordinates the environmental measurements in the vicinity of the damaged plant.

IRSN has 1700 employees with 1000 specialists over a large spectrum of disciplines: sciences for engineer, biology, medical sciences, ...

Furthermore, to develop its own capacity of expertise, IRSN spends nearly half of its budget in research and development in nuclear safety and radiation protection. It has its own experimental platforms in a number of domains and has a specific access to experimental nuclear facilities operated by the French "Commissariat à l'énergie atomique et aux énergies alternatives" (CEA), such as the CABRI and PHEBUS reactors in Cadarache.

The licensing process involves the operators, the ASN, the IRSN, which analyzes the safety demonstrations provided by the applicants, and advisory groups of experts ("Groupes permanents d'experts"), which review the analyses made by the IRSN. Then, the final decision to grant a license to the operator, with possibly some reservations, is taken by the ASN on the basis of the technical and scientific opinions and recommendations of the IRSN and the results of their reviews by the advisory groups of experts.

There is no time limitation to the licenses, but as already mentioned, the TSN act imposes a review of the safety of each installation every ten years.

In France, the regulatory requirements are not as developed as in other countries, mainly for historical reasons. Indeed, there is a unique operator of the NPPs, EDF, and a unique constructor, AREVA, formerly FRAMATOME. Therefore, the analysis of the safety files provided by EDF is, by far, more than just checking conformity to technical requirements. The IRSN experts review all the technical documentation and focus their analysis on safety-relevant points of interest, performing, when they judge it necessary, counter studies often using computer codes developed by the IRSN, such as the ASTEC core meltdown accident simulation code [1]. They examine all the defense lines during all the lifetime of the installations, from their conception up to their decommissioning:

– verification of the conformity of the installations to the design basis, assessing their reliability and robustness;
– examination of the behavior of the installations if facing postulated incidental situations, to check that they will remain within the authorized domain of operation;
– assessment of core damage frequency in case of postulated accidents to appreciate the measures taken for preventing core from meltdown;
– assessment of the means to mitigate the consequences of possible severe accidents.

The efficiency of the analysis process mainly relies on the competence of the IRSN experts, their excellent knowledge of the installations as well as of the operating experience, and the quality of the technical dialog with EDF engineers.

3. The major safety improvements in French NPPs

The analyses of the IRSN experts have contributed to making plants safer. Some examples are given below as illustrations.

The analysis of the first line of defense has led IRSN to recommend specific non-destructive examinations and to check design calculations of structures and components important for safety. These controls have sometimes shown the necessity to reinforce them, as was the case for the structures supporting the safety injection water tank in the Bugey plant in 2000.

The analysis of power reactor accidents has shown that they might have been avoided if some precursor incidents, which occurred in other NPPs, had been taken into account. Therefore, all operating incidents important for safety, in France as well as in the international nuclear community, are analyzed independently by EDF and IRSN in order to identify any design or operation weakness, precursors of a severe accident. This has been, for instance, the case of the temporary loss of external AC power at the Bugey (France, 1984), Maanshan (Taïwan, 2001) and Forsmark (Sweden, 2006), which has resulted in reinforcing the protection of external AC power and in increasing the redundancy of the alternative AC power sources.

After the TMI2 accident, five procedures [2], named “H” and standing for “hors dimensionnement” (beyond-design accident situations), were developed to manage such abnormal situations as the loss of the heat sink (H1) or station black-out (H3) for plausible durations. The “H1” procedure was used in 2009 at the Cruas plant where debris transported by the Rhône River blocked the pumping systems causing the total loss of heat sink for about 10 hours. The use of the water stored in a tank, as planned by the “H1” procedure, allowed one to cool the secondary side of the steam generators, thus removing safely the residual heat from the reactor during the time needed by the operator to restore the heat sink. It is worth noting that this incident occurred after a cumulated time of 1500 plant operating years in France, whereas its frequency was previously ranked at 10^{-5} per plant operating year. This illustrates the difficulties in assessing the frequency of external aggression and the resulting uncertainties.

Likewise, after the flooding of the Blayais power station in 1999, where some safety functions were temporarily lost, the IRSN analysis contributed to improving the assessment of such situations for all the French NPPs and to identifying the corresponding measures of prevention, outside the sites, by raising the dam elevation appropriately, and inside the plants, by implementing cofferdams around the rooms containing safety relevant equipments.

The analyses by EDF and IRSN and the results of R&D on severe accidents performed after the TMI2 accidents (Probability Safety Assessments level 1 and 2, the international IRSN PHEBUS program [3,4] on severe accidents, ...) have resulted in many safety improvements of the NPPs in France. For instance, new materials were developed and implemented:

– systems to reliably depressurize the primary circuit and avoid possible direct containment heating;
– passive hydrogen autocatalytic recombiners to reduce hydrogen concentration in the containment and reduce the threat to the containment function;
– a containment filtered venting system to avoid damaging the containment in case of failure of the spray system.

The already mentioned “H” procedures were completed by accident management procedures, called “U”, such as the U5 which calls for venting the containment through filters if, 24 hours after the onset of core meltdown, the pressure inside the containment has risen too much. The filter performance is of 99.9% for the aerosols (such as Cs). But it is far less effective for molecular iodine and not at all for organic iodine, which is today a subject of research.

These accident management procedures, and the corresponding equipment, are now part of the “beyond-design” safety demonstration and are still being progressively improved according to the progress made in understanding the phenomena and in technology. For instance, at the occasion of the third periodic safety review of the 900 MWe NPPs, new detectors, such as hydrogen measurements, or vessel failure detectors, will be implemented on these plants in the coming years. The occurrence of the Fukushima accident will likely foster the implementation of them on all other plants.

Discussions between French and German safety organizations led to the definition of ambitious general safety objectives [5] to be applied for the power reactors to be constructed in the early 21st century, so-called Generation III plants. There were approved in 1993 by the German and French Nuclear Safety Authorities. They call for a significant improvement of the reactor design, in order to achieve significant reductions of:

– the global core damage frequency;
– the potential radioactive release due to all conceivable accidents, including core meltdown accidents.

The first objective implies that improvements in the defense-in-depth should result in a global core damage frequency of less than 10^{-5} per plant operating year, uncertainties and all types of failures and hazards being taken into account.

The second objective implies that accidents leading to early and large radioactive releases have to be "practically eliminated", i.e. if they cannot be considered as physically impossible, design provisions have to be taken to make them impossible. Should any radioactive release occur, it must be late and limited in such a way that it would necessitate only very limited protective measures in terms of area and time for the public: no need for emergency evacuation, limited sheltering, and no long-term restrictions in consumption of food outside of the immediate vicinity of the plant.

On the basis of these objectives, the IRSN contributed in the elaboration of the technical guidelines, which were endorsed by the French and German advisory groups of experts and approved in the early 2000s by the ASN. They imply the reinforcement of the defense-in-depth principle as compared to Generation II plants. More extensive considerations have to be given to possible multiple failures and the use of diversified means to fulfill the fundamental safety functions. In addition, substantial improvement of the containment function is needed.

These guidelines are currently being used as the reference to the design and the safety assessment of the EPR (European Pressurized Reactor) being constructed in Flamanville.

It is also worth noting that WENRA (the Western European Nuclear Regulators' Association) has adopted these safety objectives for all new reactors in November 2010.

In 2009, EDF has informed the ASN that it was intending to seek license for extending the duration of the operation of the currently operating PWRs significantly beyond 40 years. The IRSN and ASN positions, before the Fukushima accident, were that significant safety improvements were then to be implemented for these plants. Since these plants would have to coexist for decades with Generation III plants, they should have a safety level as close as reasonably possible to theirs. In IRSN's view, the Fukushima accident fully illustrates the pertinence of this position.

4. The impact of the Fukushima accident in France

On 23 March 2011, the French Prime Minister asked the ASN to organize a complementary safety review of French NPPs. The same decision was taken a few days later by the European Council, asking for the so-called "stress tests". The specification of the complementary safety review was based on a proposal that WENRA issues on 21 April, which was also used to define the European "stress tests". The ASN decided to extend this review to test material reactors and experimental reactors, as well as to the nuclear facilities of the fuel cycle, such as the La Hague reprocessing plant.

The general objective of the complementary safety review was to analyze in a deterministic manner the behavior of nuclear installations when subjected to postulated accidental conditions well-beyond their design basis, in terms of load and duration of the load. It was also required to investigate the measures which could be taken to face such situations and limit the consequences of the accident on the environment and the public. It includes 3 main topics [6]:

– the evaluation of the robustness of the plants to external hazards;
– the evaluation of the robustness of the plants to durable loss of power or/and to durable loss of heat sink;
– the evaluation of the robustness of the severe accident management measures.

The external hazards to be considered were:

– earthquake;
– flooding;
– accumulation of earthquake and induced flooding;
– extreme climatic events.

A progressive approach was to be considered, describing the design basis domain, assessing the existing margins, when increasing the load and/or its duration with respect to the loss of safety functions and to possible "cliff-edge effects", such as core damage (or criticality for fuel cycle facilities) and release of radioactive products into the environment.

The same approach was to be applied for the loss of power and the loss of heat sink, and the accumulation of both, on a power reactor, but also on a site, as some emergency equipment can be common to several power reactors on a same site, or damaged reactors can make intervention on neighbor reactors more difficult.

As for severe accident management, the operators had to describe all the provisions planned to prevent and manage a core meltdown accident, assess their robustness in extreme situations (earthquakes, flooding), the delay before core melt and radioactive material release.

For the power reactors, the analysis was also to be applied to the behavior of the spent fuel storage pools, as they obviously can form weak points under certain circumstances.

The French operators (EDF, CEA, AREVA and ILL) had until 15 September 2011 to send their evaluations to the ASN. Then the IRSN experts have analyzed all the reports and presented their first conclusions and recommendations for review by the advisory groups of experts on 8–12 November. The ASN will then give its position in December 2011.

All the national reports will be reviewed by peers in spring 2012 and the results will then be presented to the European Council in June 2012.

This complementary safety review has requested a huge effort to the operators, but also to the IRSN, which has analyzed all the reports sent by the operators with a critical eye, based on a defense-in-depth approach. Preliminary conclusions show that the continuous safety improvement process used in France has already contributed to make the French plants more robust than they were at their construction. However, as expected, the need for significant safety improvements has been identified, in particular to respond to beyond-design situations. A core of vital equipment for the control of the safety functions will be determined. It will be composed of equipment present on the plant or on the site to cope with the first 24 hours, complemented by mobile means transported on the site in the 24 hours following the onset of the accident. This core of equipment must be highly protected to face extreme situations even of extremely low probability. The ultimate goal is to prevent core meltdown, or if unsuccessful, to limit the release of fission product into the environment to the lowest level reasonably possible.

5. The necessary international cooperation between TSOs

As shown above, nuclear safety and security, and radiation protection must not be static and their constant evolution is dependent upon progress in science and technology. It is therefore necessary to develop a high level of expertise capability at the service of the regulatory bodies. In France, the choice has been made to create for this purpose a TSO, namely the IRSN.

As described earlier in the article, this capability is built on research and scientific analysis of the operating experience. However to be efficient, this organization requires appropriate resources in manpower and funds, and capacity to train new generations of experts. This is the reason why years ago some TSOs in Europe decided to join their efforts in networking their capacities in ETSON [7], the European TSO Network. It is composed of GRS (Germany), BelV (Belgium), IRSN (France), VTT (Finland), UJV (Czech Republic), VUJE (Slovakia) and of SSTC (Ukraine) as an associated member. JNES (Japan) has joined ETSON as an associated at the end of November 2011.

The main objectives of ETSON are to harmonize the methods of safety analysis, to manage knowledge, to discuss the priorities in safety research and to organize the training of new generations of experts. With regard to the research priorities, ETSON is a member of the European research platform in nuclear technology, SNE-TP, sponsored by the European Commission. The main objective of this platform is to elaborate the European strategic research agenda in nuclear technology for the years to come. The fact that most TSOs are represented by one single entity allows them to express more strongly their position on research priorities in nuclear safety [8], balancing the weigh of the industry. In the aftermath of the Fukushima accident, ETSON members are examining how they can progress together in case of an emergency, trying to harmonize practices, to ease information exchanges and to pool resources for mutual assistance.

This need for networking TSOs worldwide is being recognized by the IAEA. The International Conference on the challenges faced by TSOs in enhancing nuclear safety and security held in Tokyo in October 2010 [9] had the objective to develop a common understanding of the responsibilities, needs and opportunities of TSOs and to further promote international cooperation and networking among them.

The Conference has strongly recommended that the IAEA fosters the establishment of a TSO forum, which would address the following issues:

- achieving scientific excellence, through cooperative research projects, co-development of analysis tools, share of knowledge and training programmes;
- addressing the scientific and technical bases necessary to conduct expertises on important topics in nuclear safety and security, such as safety of Generation III power plants, aging, effects to low dose exposures, … ;
- facilitating the international availability of state-of-the-art expertise resources in nuclear safety and security, and the radiological emergency response;
- contributing to the worldwide harmonization of nuclear safety practices on the basis of the highest standards;
- fostering the reciprocal provisions of training, assessment and peer review.

These recommendations were issued before the Fukushima accident, when the “nuclear renaissance” was currently evoked by many countries already operating nuclear power reactors, but also when NPP projects were considered for construction in “embarking” countries.

If the Fukushima accident has somewhat tempered the move towards the construction of new plants in some countries, others deciding to shutdown their plants in mid-term, the opinion of IRSN is that the need for networking TSOs is even stronger than before. Indeed, lessons from the accident have to be drawn with a large consensus in order to make the operating NPPs more robust to all type of hazards and thus enhance nuclear safety worldwide.

6. Conclusions

France has adopted since several years a continuous safety improvement approach, in particular at the occasion of the periodic safety reviews of the nuclear installations, based on the analysis of past accidents and on operating experience. This approach has contributed to make the French power reactors more robust than they were at the time of their design. With Germany, France has also contributed to define more ambitious safety objectives for the new reactors to be built in Europe.

From IRSN point of view, the Fukushima accident has shown how important such an approach was and the first lessons drawn from this event are used to make the plants even more robust when subjected to extreme situations not taken into account in the design basis. Furthermore, no doubt that the Fukushima accident will foster the implementation of the identified safety improvements on the operating plants.

To be efficient, such an approach needs a contradictory dialog between the operators on one hand and a public body of highly competent experts on the other hand, as safety is based on progress in science and technology. In France, this is the IRSN, a TSO, which plays this important role.

Forming and maintaining the competence of a TSO needs large resources. Networking of TSOs is an appropriate response to share knowledge, perform cooperative research, review safety analyses practices and organize training of new generations of experts. It is in progress in Europe trough ETSON and the IAEA is considering creating the TSO forum to extend the European initiative worldwide. This is an efficient way to enhance and harmonize nuclear safety worldwide.

References

[1] J.-P. Van Dorsselaere, C. Seropian, P. Chatelard, F. Jacq, J. Fleurot, P. Giordano, N. Reinke, B. Schwinges, H.J. Allelein, W. Luther, The ASTEC integral code for severe accident simulation, Nuclear Technology 165 (3) (2009) 293–307.
[2] E. Raimond, J.-M. Bonnet, G. Cenerino, M. Dubreuil, F. Pichereau, J.-P. Van Dorsselaere, Continued efforts to improve the robustness of the French Gen II PWRs to the risks of severe accidents. Safety assessments and research activities, in: EUROSAFE Conference, Paris, France, 7–8 November 2011.
[3] B. Clément, et al., Thematic network for a PHEBUS FPT-1 international standard problem (THENPHEBISP), Nuclear Engineering and Design 235 (2005) 347–357.
[4] Ph. March, et al., First results of the PHEBUS FPT-3 test, in: Proc. of the International Conference on Nuclear Engineering, ICONE 14, Miami, USA, 17–20 July 2006.
[5] J.-M. Evrard, F. Féron, The development of safety objectives for new nuclear power plants in France, in: IAEA Technical Meeting on Safety Goals, Vienna, Austria, 11–15 April 2011.
[6] E. Raymond, K. Herviou, C. Lavarenne, After the FUKUSHIMA accident: which challenges for the NPP design and accident management? Some IRSN views from the French situation, in: ECSNI-WG-GAMA Annual Meeting, OECD Headquarter, Paris, France, 9 June 2011.
[7] European TSO Network web site: http://www.eurosafe-forum.org/formation-european-tso-network.
[8] G. Bruna, et al., The TSO's position on safety research to be performed over the next decade, in: EUROSAFE Conference, Paris, France, 7–8 November 2011.
[9] J. Repussard, Conclusions of the international conference on the challenges faced by Technical and Scientific support Organizations (TSOs) in enhancing nuclear safety and security, President's report, in: IAEA Meeting, Tokyo, Japan, 25–29 October 2010.