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IRSN
INSTITUT DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

ANTICIPATION AND RESILIENCE

CONSIDERATIONS A DECADE AFTER THE FUKUSHIMA DAIICHI ACCIDENT

MEMBRE DE
ETSON

THE PUBLIC EXPERT ON NUCLEAR AND RADIOLOGICAL RISKS

IRSN's mission includes providing expertise, research projects, protection, planning for the future, and sharing resources to the benefit of the French public authorities and the public at large.

IRSN can boast the unrivalled capacity to combine the expertise of researchers and experts in order to plan ahead for the questions of the future about nuclear and radiological risks changes and how to control them.

IRSN teams aim to ensure that society at large is aware of their works and can share their knowledge. With this approach, they help to improve a wide access to information and boost dialogue with stakeholders.

IRSN contributes to French public nuclear security and safety policies, as well as health, environmental and crisis management policies.

As a public industrial and commercial establishment supervised jointly by the French Minister of the Environment, the French Minister of Defence, and the French Ministers of Energy, Research and Health, IRSN comprehensively integrates its initiatives in the Government's modernisation policies with its risk management approach and by implementing a CSR policy.

IRSN HAS AROUND **1,770 EMPLOYEES**

including many engineers, doctors, agronomists, veterinarians, technicians, experts and researchers.

To carry out its missions, IRSN has AN ANNUAL BUDGET OF AROUND

€275 million

"Accidents appear to be the result of highly complex coincidences which could rarely be foreseen by the people involved. The unpredictability is caused by the large number of causes and by the spread of information over the participants… Accidents do not occur because people gamble or lose, they occur because people do not believe that the accident that is about to occur is at all possible."

Wagenaar and Groeneweg, 1987

EXECUTIVE SUMMARY

On March 11, 2011, an earthquake of very high magnitude (M=9.1) off the coast of Tohoku province in Japan caused a tsunami of an unprecedented magnitude, devastating part of the east coast of the island. Several nuclear power plants (NPPs) were affected by these events. At the Fukushima Daiichi NPP, the disaster could not be avoided: the fusion of the cores of three reactors resulted in radioactive releases into the environment that led to lasting contamination of the territories and very heavy psycho-social and economic consequences for the populations living near the site and for the entire country. This accident also had an impact on the general state of health of the people most affected.

Like the accidents at the Three Mile Island NPP in the United States in March 1979 or at the Chernobyl NPP in the USSR in April 1986, the Fukushima Daiichi accident of 2011 marked the history of civil nuclear power and nuclear safety. Each of these accidents had a significant impact on the development of safety approaches aimed at preventing accidents and defining provisions to limit their consequences as much as possible, on the preparation and management of emergency and post-accident situations, supported by the continuous improvement of knowledge in safety and radiation protection.

Each accident has been analysed, the safety demonstration of the facilities has been completed, new research programs have been initiated to improve knowledge, and measures have been taken to ensure that it doesn't happen again. However, although necessary to prevent events previously unimagined or not taken into account, this approach is more reactive than proactive. Ten years after the accident at the Fukushima Daiichi NPP, at a time when new measures have been defined to improve the safety of French nuclear facilities, it is important to look back at what this accident, like others before it, teaches us about our ability to anticipate, our ability to identify signs that could call into question the approaches adopted to control risks or their implementation. What does it teach us about our state of preparedness to face a major accident and manage its consequences in the short, medium and long term?

The degradation of the safety of nuclear installations can be insidious; it is essential to remain attentive, at all times, to all signs that could reveal a drift in this area. The absence of any serious incident or accident in recent years should obviously not lead us to consider that safety has been achieved, as it is never definitively achieved. On the contrary, it is necessary to continue the efforts undertaken for many years in the field of nuclear safety and radiation protection, to more effectively exploit and share experience feedback from the operation of installations, to ensure the proper application of existing safety approaches and to develop new ones, particularly in the treatment of rare events with potentially severe consequences, for which expertise cannot be based solely on established and definitive knowledge.

Assessing risks and evaluating their impact according to various hypotheses is, in a situation of high uncertainty, highly complex. The current pandemic illustrates this all too well. There is still room for improvement in risk assessment, in the understanding of the behaviour of installations in the event of an accident, in the evaluation of the consequences of accidents, and in determining how best to manage them. This must be done collectively, with the participation of all the relevant stakeholders.

This primarily involves a more efficient use of experience feedback, based on systemic approaches to better account for the complexity and dynamics of the interactions between the various components (human, organizational, technical, and managerial) that contribute to risk management. The aim is to gain a better overall appreciation of the factors that facilitate or, on the contrary, are likely to disrupt the deployment of the risk control measures chosen. Models must be developed based on knowledge of the processes involved in the design and operation of nuclear facilities. The new digital tools that have emerged in recent years offer new opportunities for analysis, exchange and sharing, which should be fully exploited.

The safety approach for nuclear facilities is built on a defence in depth concept, based on the ability to anticipate risks and limit the consequences of situations considered plausible. The application of this approach must always be improved, and the compliance of the installations with the associated requirements must be ensured on a permanent basis. The accident at the Fukushima Daiichi NPP nevertheless raises questions about the ability to anticipate combinations of events and failures likely to affect nuclear installations, particularly rare events whose consequences may be severe. Assessing the risks associated with these situations remains difficult because the more unlikely the situations under consideration, the greater the uncertainties, and no approach can completely rule out their occurrence. The development of new, multidisciplinary approaches must make it possible to advance in the knowledge of these phenomena and the associated risks, in particular those which may result from natural hazards. In addition, in order to better address the diversity of real situations that may occur and their potentially unexpected nature, it is necessary to strengthen the response and adaptation capacity of people and organizations to foster the conditions for resilience.

Like the one at the Chernobyl NPP before him, the accident at the Fukushima Daiichi NPP confirmed, if necessary, the complex and multidimensional nature of recovery after a nuclear accident, which affects territories and populations for decades. At every stage, the management of such a situation must involve the affected populations. Initially, this will mean involvement in the radiological characterization process (e.g. possibilities to take measurements in the context of shared expertise) and then in the decision-making process regarding living conditions. In any case, the intervention of experts must obey ethical principles, in particular respect for the autonomy and freedom of choice and decision making of the persons affected.

In any event, evacuation, one of the actions to protect populations in the event of an accident, requires preparation, as it profoundly affects the living conditions of the evacuees, whether they are volunteers or not. For its part, the lifting of evacuation orders creates a difficult choice for the affected inhabitants. Ten years after the accident at the Fukushima Daiichi NPP, the return rate of the inhabitants is about 20%.

To be ready to manage an accident at a nuclear facility and its consequences, in the emergency or recovery phase, emergency exercises help professionalize experts and contribute, in the event of an emergency, to individual and collective resilience in the face of an unexpected situation. The ongoing efforts to make these exercises more realistic should be sustained: longer exercise length, involvement of a greater number of participants - particularly from the civil society -, more unexpected scenarios, more extensive deployment in the field of equipment and people to characterize the contamination of the environment, people and property, strong media pressure...

This report is intended for anyone interested in nuclear safety issues, and more generally in risk management in any capacity, whether public or private decision-makers, institutional or non-institutional experts, members of the public, etc. It invites us to examine current practices in these fields, how each actor contributes to the risk management of nuclear installations, and the need to develop other approaches to better assess the risks, both in the context of normal operation of installations and in accident situations. Better assessment to prevent nuclear accidents, better preparation to handle them if they do occur, which cannot be excluded: it is the responsibility of the experts, including IRSN, to continue the discussions, to improve knowledge, and to develop new, more systemic approaches. The purpose is to enable decision-makers to make "well-informed" decisions in view of the challenges of the protection of the people and the environment, and the safety of the installations.

This report has no other ambition than to propose a few ideas to encourage discussions to this end.

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1 EXPERIENCE FEEDBACK: A WEALTH OF INFORMATION WHICH MUST BE BETTER USED

Experience feedback is intended to allow parties to learn lessons from events affecting nuclear facilities in order to improve their performances, particularly in terms of risk control. The accident at the Three Mile Island nuclear power plant in the United States in 1979 led to increasing international concern over experience feedback and closer attention being particularly paid to early warning signs. It was then accepted that an accident can be caused by a series of multiple material, human or organisational failures, and that these failures can occur during minor incidents which can be handled in a manner which triggers far more serious accident scenarios. Since this time, experience feedback has been repeatedly exchanged at national and international level. And how is experience feedback handled today? Can the approach be improved, and how?

“The accident” and safety improvement

Safety can primarily be improved thanks to technical progress based on knowledge obtained, particularly from past accidents. Such knowledge is then used to reconsider the design of the facilities currently in use and those in the development phase. This approach was applied to the accident at the Three Mile Island (TMI) nuclear power plant (NPP) and led to multiple improvements to safety at French nuclear power plants: the operation of facilities and associated instrumentation, the confinement of radioactive substances, the deployment of emergency plans, etc. Many safety investigations were carried out after this accident, and particularly focused on severe accidents, and probabilistic safety studies were widely developed, leading to significant improvements to safety many years later, e.g. for reactor shutdown states. In the same way, complementary safety assessments[1] (CSA), carried out at all basic nuclear facilities in France within one year of the accident at the Fukushima Daiichi NPP in 2011, led to the definition of a "hardened safety core" concept comprising a certain number of items of equipment which can be used to manage extreme natural risks, and progressively adapted to the different types of nuclear facilities.

These historical accidents have provided lessons on how to structure technical approaches, highlighting "socio-technical" aspects of nuclear safety, i.e. those which integrate interactions between equipment, personnel and organizations. On this basis, the analysis of the Three Mile Island NPP accident highlights the importance of "human factors" and has led to many types of progress in terms of the structure of operational teams (introduction of a safety engineer), the ergonomics of control rooms and operating procedures, and crisis management. After the Chernobyl NPP accident in 1986, organisational, managerial and "cultural" aspects of risk management were reconsidered, particularly decision-making processes and the importance of arbitrating safety concerns and other types of concern. After the Fukushima Daiichi NPP accident, improvements programmes focused on external hazards, any combined external hazards, and short-, medium- and long-term emergency and recovery management. **In parallel, more political issues relating to "risk management" arise.**

Risk management and the control of the nuclear industry were already considered in this way before, to varying degrees depending on the country (Tokaï Mura accident in Japan in 1999[2], and the near-miss at Davis Besse in the United States in 2002[3]). In France, the media and political crisis in the wake of the Chernobyl NPP accident in 1986, followed by health crisis in the 1990s (contaminated blood, mad cow disease, etc.) have progressively modified the French nuclear safety and radiation protection system. Many years later, these changes led to the creation of a government appraisal body, operating independently to industry (IRSN, in 2002) and a safety authority, operating independently from public authorities (ASN, in 2006).

The impact of the different factors in nuclear safety, whether technical, socio-technical or socio-political, has constantly varied based on the lessons learned from each of these major accidents. In 2020, safety is no longer considered as merely the

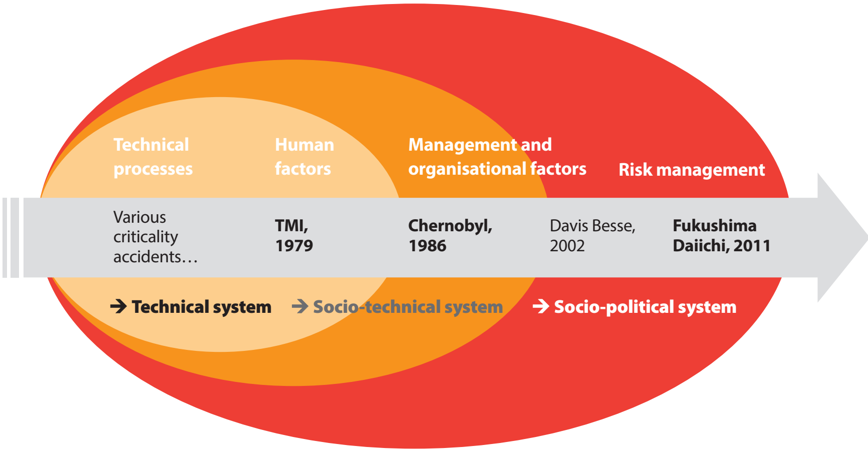
1 European stress-tests.

2 On 30 September 1999 at Tokai-Mura in Japan, a "criticality" accident took place at a uranium processing plant operated by Japan Nuclear Fuels Conversion Company (JCO): nuclear chain reactions were triggered in uncontrolled conditions, releasing radiation and radioactive gases and severely irradiating several workers, two of whom did not survive. The accident was brought under control around twenty hours after it started.

3 The vessel head of one of the power plant's reactors was found to be seriously damaged by the metal corrosion of penetrations, caused by boric acid.

result of the technical reliability of facilities. Will these changes to nuclear safety lead to the improved characterisation and prevention of accidents, and limit the inherent consequences? Is it besides necessary to characterise the accident in order to plan ahead for solutions?

Figure 1: Variation in the weight of the different components of nuclear safety.



Experience feedback and sharing information internationally

After each major accident, the limits of plausible scenarios are pushed slightly further back. To what extent could the events behind the accident have been planned for?

According to the international experts assigned by the Committee on nuclear regulatory activities (CNRA) of the OECD Nuclear Energy Agency, in 2019, "*almost all recent significant events reported at international meetings had already occurred in some form or other*"[4]. A similar conclusion had been reached in 1979, when analysing the TMI accident: the report by the Kemeny investigation board indicated that several earlier incidents could have been considered as "warning signs", however these incidents were not sufficiently analysed. In addition, the lessons learned were not widely advertised, or were not communicated early enough. To give just one example, a similar incident had

4 https://www.oecd-nea.org/jcms/pl_14142

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occurred at Beznau, in Switzerland, in 1974, on a reactor designed by Westinghouse, however no information was provided to either the US authority or the rival designer, Babcock and Wilcox, designer of the TMI reactors. In 1977, a serious event occurred at the Davis Besse power plant in the United States, with exactly the same scenario than the one at TMI two years later. However, at TMI, operators understood what was actually happening too late to prevent the core from melting down.

At the time, it was considered that "*if the event had no real consequences, it was not important*". International transparency and the sharing of experience were then determined as contributors to improving safety, as well as the facility design policy, based on the defence in depth concept, or research. On this basis, the near-misses at Davis Besse (United States, 2002) and Barsebäck[5] (Sweden, 1992) had significant consequences in many countries, firstly on the replacement or reinforcement of the operational monitoring of primary side components produced using nickel alloys (trade name: Inconel), and secondly on core cooling systems in accident conditions.

However, are such events systematically considered as important when handling experience feedback?

The design basis of facilities were reconsidered after the Fukushima Daiichi NPP accident, based on extreme events and, more specifically, combined natural hazards. This question was also clearly on the table in France, after the partial flooding of the Blayais power plant in Gironde in December 1999. Physical changes (raised levees, provisions to protect rooms housing safety equipment from flooding, etc.) and organisational changes (special operating rules[6], changes to operator emergency plans[7]), and later the launch of formal safety requirements (creation of an ASN flooding guide published in 2013), were the main result of experience feedback from this "incident" (the flooding led to the loss of several safety systems) for all basic French nuclear facilities. In fact, the partial flooding of the Blayais power plant and how operators and French safety bodies handled this flooding only appear to have been noticed (or rediscovered) at international level after the Fukushima Daiichi NPP accident, despite the fact that the lessons learned from this event in France were presented at several international conferences. In June 2011, the Fort Calhoun power plant in the United States was largely

5 A steam leak on the boiling water reactor cooling system damaged the cladding on nearby pipes, carrying the fibreglass to the back of the building. The fibres clogged the filters at the core cooling pump inlet.

6 Flooding particular operating procedure: operating rule aiming for example to reinforce protective provisions at sites if flooding is forecast.

7 Consideration of events likely to affect all facilities at one single site.

flooded after the Missouri river reached high water levels. Why weren't the lessons learned from the Blayais incident in France taken into greater consideration outside of the country? In the same way, can we consider that events around the world have been analysed appropriately in France?

The Blayais incident is not a one-off example, and reflects the difficulties inherent in processing and transmitting experience feedback at international level. In order to be identified as a "source of shareable improvements", lessons learned from experience feedback must be considered as transposable and refer to issues which industrial firms and regulating authorities view as worth investing in, in terms of engineering, research, etc. On the other hand, it would appear that, if the topic raised is too specific (to the power plant site, to the power plant technology, to local weather conditions, to an operator's organization, or even, more generally, to the "assumed" culture[8], etc.), the lessons learned will be deemed too complex to use and apply generally, as the scope is off the beaten path and the assumption must be made that similar events could occur at other facilities, at other locations, with other technologies, and with other organisational cultures.

Towards a more effective treatment of experience feedback?

A question of time

Learning lessons from major accidents or key events is frequently a time-consuming process and applying safety improvements can take even longer. While initial technical conclusions can frequently be rapidly identified, as was the case after the Fukushima Daiichi accident, a more in-depth analysis of experience feedback and events is required, considering the full level of complexity inherent to the many different aspects at play (technical, human, organisational, managerial and political factors), in a context of different dynamic trends. This process frequently leads to technical or organisational modifications, deployed over years, or even decades, after the completion of research and development works and studies.

In this context, how can we be certain to reach all possible conclusions from the available information after an accident when media and political pressure often push

8 The concept of "safety culture" arose after the Chernobyl NPP accident to indicate the relationship between the accident and the "assumed" intrinsic Soviet regime culture, however this culture has never been seriously analysed or characterised.

operators to implement rapid material and organisational modifications and authorities to require improvements in the shortest possible time-scale? Once initial analyses have been completed, and the initial improvements required identified, how can we ensure the continuity of experience feedback, whose timeframes are sometimes incompatible with the sustained pace of safety assessments and industrial imperatives?

In short, urgency should not obscure the fact that it is also necessary to take the time for analysis, to draw all the relevant lessons from an accident, in order to avoid a similar scenario happening again or that factors that proved to be key factors in the aggravation of a situation could once again be triggered.

Gaining knowledge and learning lessons

Experience feedback from incidents and accidents undeniably represents a wealth of information for improving the safety of nuclear facilities. However, it takes strength of character to use this information effectively and appropriately. It is important to not simply issue preliminary conclusions and analyses, which are frequently fragmentary and could downplay the root causes of events and provide incomplete explanations: equipment failure, operator error. More in-depth questioning is necessary to avoid masking any potential transpositions and inhibiting the general nature of the lessons to be learned, but this process takes time and data on how the event occurred must be collected.

Matters such as how on-site teams managed the situation, during the Fukushima Daiichi NPP accident, finding back-up solutions while exclusively using resources available on the site, and reaching decisions with potentially tragic consequences, must all be studied and conclusions can only be reached on the basis of precise data reflecting the actual situation in terms of the intentions, decisions and actions of all operators. Research in humanities and social sciences launched after the accident on this basis is starting to bring in knowledge. This knowledge must be used to further deepen the analysis of the accident.

The same applies for "incidents" (renamed "significant events" in the early years of this century) which require formal and regulated declarations. Once again, a wealth of information is available and the conclusions reached must not simply refer to technical aspects. These events are "monitored" as non-compliances, they are analysed as warning signs, reliability data for equipment used in probabilistic studies is updated, studies are launched, as well as research, potentially. However, they must be more extensively used as input to further knowledge of how French facilities operate, operating difficulties, both material and organisational complexities, which will all lead to operating limitations and negatively affect the workers performing these tasks on a daily basis.

These events are often systemic, and analysis must take this fact into account. Causal relationships are not linear, static or pre-determined in actual accident situations, even if post-accident reconstructions can give this impression. The socio-technical systems involved are too complex and dynamic for such an assumption. A systemic approach is required in order to incorporate this complexity and the interactions between the different system components, and ensure that the analysis is pertinent. **Accident analyses must not simply involve the identification of independent causes, but attempt to understand the bigger picture.**

"Models" must be developed for this purpose, based on current knowledge of the phenomena influencing the management of design and operating phases for nuclear facilities: which factors help to control risks? How do they occur? With this approach, the event must not be considered as a "non-compliance" to be recognised, requiring an ad hoc correction based on the direct and visible causes (local design fault, "undisciplined action", "inadequate skills", etc.) for which a party or a group is responsible. The event is the outcome of the failure (or success, as the event is detected and declared) of lines of defence, which, although not systematically identified as such in the safety analysis reports provided by operators, help to control risks. The aim is to identify and understand decisive factors, which disturb or simplify the implementation of the risk control provisions selected by the socio-technical system. Actual "root causes" can be identified using a systemic approach to incidents and accidents. The aim is not to conclude that professionals make mistakes, but rather to identify which factors led to the errors identified (missing or incorrect information, not enough time allocated to a task, unshared targets, unsuitable tools, etc.), over and beyond assumed individual characteristics (skills, cognitive bias, motivation, fatigue, miscellaneous ability, etc.).

The safety of facilities and operations can clearly be sustainably improved by influencing these causes, over and beyond the benefits of technical conclusions alone.

Opening up to conclusions from other sectors in order to consolidate analysis reference documents

In the same way, it is essential to learn lessons from incidents and accidents in other sectors in order to add real-life reports to experience feedback. Should the historical barriers between industrial segments be considered as obstacles to sharing conclusions reached based on these accidents?

Some industrial accidents in France, such as the explosion at AZF (Toulouse, 2001), the derailing at Brétigny-sur-Orge (2013) or the fire at Lubrizol (Rouen, 2019), provide examples of sources of experience feedback on maintenance policies, the effects of successive restructuring programmes, inspections and compliance with regulations, not forgetting emergency management and communications. Remarkable analyses focused on the accidents involving the NASA space shuttles in 1986 (Challenger) and 2003 (Columbia), and identified the factors which led to these accidents, and which can also be found in many incidents or accidents in the nuclear field.

Some conclusions could undoubtedly be transposed to the nuclear sector. Accident analyses can lead to a number of helpful concepts in relation to "minor" incidents and "major" accidents. For example, concepts such as *the normalisation of deviance, the reversal of responsibility for providing proof* in decision-making processes, *organisational complexity and bureaucratisation* triggered by a plethora of rapid changes, could be used to a greater extent to characterise the root causes of tangible non-compliance.

Using new technologies to analyse experience feedback and pass on information

New digital tools have emerged in recent years, complementing the strict methodology required for the analysis of experience feedback, and offering new options for analysis, exchange and sharing.

Artificial intelligence, particularly machine learning, and natural language processes (for processing input data in the form of "stories" of events) are currently offering a clear means of improving analyses. We can now construct operational analysis support systems for experts, but also decision-makers. Despite this, algorithms cannot replace experts, "weak signals" can only be identified from an in-depth analysis of events, and the technological, methodological and organisational conditions for success must be under control in order to achieve actual results.

Thanks to technological progress over the last decade, new solutions exist for sharing information at national and international level. Clearly convenient means of communication now exist to simplify virtual meetings. But the real progress lies in the visualization of information and knowledge to be shared. It is indeed fundamental to be able to present data in an intelligible way (despite constantly-increasing volumes). Concepts such as storytelling appear entirely appropriate, and aim to communicate information on events and accidents while boosting the history records.

Multiplying and diversifying sources of expertise, and creating extra opportunities for sharing, have been targets for many years, and the methods and tools being developed today must lead to yet more improvements in this respect.

Experience feedback must look at what is visible but also at what is not, as well as factors which take longer to identify, information which is not directly accessible must be obtained and subjected to a fresh and systemic view, taking a step beyond a mere technical understanding of how the accident occurred, which is certainly necessary but not sufficient.

If we take a look at the past 40 years of history, there have been significant improvements, particularly after the most notable incidents, and accidents. In hindsight, it is also possible to identify situations and incidents which should have been analysed in more detail, and shared more widely, to enhance safety. The conclusions reached today based on a serious accident, could also have been reached by considering other, less visible, less dramatic, less media-worthy, events. This is true for many reasons: the number of events, the potential for general application, the time available for their treatment, the analytical shortfalls of the socio-technical system as a whole.

Lessons learned based on experience feedback from events are still currently over-focused on technical aspects, and do not systematically consider all factors involved in risk control or lack of risk control.

2 ROBUSTNESS OF FACILITIES AND ABILITY OF PERSONNEL AND ORGANIZATIONS TO RESPOND TO UNEXPECTED SITUATIONS

A nuclear facility must be designed and operated in compliance with a set of rules intended to control risks and protect the populations and the environment in a satisfactory manner. The accident at the Fukushima Daiichi nuclear power plant (NPP) raised the question of whether or not we can plan ahead for any events likely to affect nuclear facilities and whether the rules and assumptions applied when designing safety systems, which were invalidated during the accident, are sufficient. Safety can be improved by reinforcing the application of the defence in depth approach, however all combinations of events and failures considered cannot be covered as design bases and it is important to ensure that design choices do not render the design and operation of facilities excessively complex, including for new facilities. At the same time, a reflection on the possibilities of better preparing people and organizations to deal with the diversity of real-life situations and unforeseen situations should be carried out.

In France, safety is defined as "*all technical and organisational provisions applicable to the design, construction, operation, shutdown and decommissioning of basic nuclear facilities, and the transport of radioactive substances, intended to prevent accidents or limit their consequences*".

The selected safety approach is based on a defence in depth approach, according to which, while provisions must be applied in order to avoid incidents or accidents as far as possible, it is nonetheless important to assume that they could still occur. The suitable means used to manage such events and limit their consequences must be studied and the appropriate provisions must be implemented.

On this basis, the defence in depth approach aims to limit the consequences on the population and the environment of human and technical failures considered as "plausible", and ensure that the barriers set up between radioactive substances and the environment stay intact. This approach provides for graduated, but solid, protection from the hazards induced by a facility, leading to the implementation of successive levels, each with an adequate degree of independence:

- *"The first level of defence is intended to prevent incidents;*
- *The second level of defence is intended to detect the occurrence of such incidents and implement actions in order to both prevent them leading to an accident and restore normal operating conditions, or, failing this, to achieve and subsequently maintain the facility in a safe state;*
- *The third level of defence is intended to control unavoidable accidents, or, failing this, to prevent worsening as far as possible by recovering the control of the facility in order to return to and maintain the facility in a safe state;*
- *The fourth level of defence is intended to manage accident situations which arise subsequent to the failure of the provisions of the first three levels of defence in depth, and lead to fuel meltdown, in order to limit the inherent consequences, particularly for people and the environment.*

In addition, a fifth level of defence in depth, covering crisis management by public authorities, aims to mitigate the radiological consequences of likely radioactive discharges in accident conditions."

Nuclear power plant reactors raise specific risks (uncontrolled nuclear reaction, fuel overheating, dispersal of radionuclides) which can be prevented if three fundamental safety functions are satisfied (controlled reactivity, fuel cooling, confinement of radioactive substances). One level of defence in depth can incorporate several successive lines of defence, with each line defined as a series of technical, human or organisational provisions, all of which contribute to controlling these specific risks for a given event and at a given level of defence in depth.

In order to effectively apply the defence in depth approach, any situations likely to affect a facility must be suitably integrated, solid lines of defence must be set up for the incidents and accidents considered, and these lines must be independent to the expected degree for any given event.

Improving the robustness of levels of defence in depth

Safety has been constantly improved thanks to experience feedback from incidents and accidents and knowledge acquired via research, particularly by considering a large number of situations over the years. These improvements have primarily led to the installation of new equipment, which is sometimes complex due to the congestion of the premises at existing facilities. We could consider the example of instrumentation and control equipment, or low voltage electrical distribution systems for the hardened safety core, which, unlike the ultimate back-up diesel generators, cannot be transferred to new premises outside of the nuclear island buildings.

Installing new equipment will also have a significant impact on facility operation, with increasingly complex technical specifications for operations (aiming to ensure that this equipment is available and defining the action to take if not) and incident and accident operating procedures, increased maintenance operations and periodic testing.

These considerations highlight that there are practical limits to the possibilities of strengthening defence in depth by adding new equipment to existing facilities, thus forcing their shutdown. It is important to avoid reaching excessive levels of complexity for facilities, or facility operation, as the effects of such complexity would be likely to reduce the safety benefits of the new equipment.

On the other hand, the robustness of the lines of defence could be reinforced by improving the ability to control facility state, and therefore maintain compliance with the applicable requirements during operation in the long-term. Each facility must indeed continue to comply with its operating reference document at all times. If a set requirement is not met, the appropriate action must systematically be taken as rapidly as possible. In fact, non-compliance is likely to weaken lines of defence in depth. Aging phenomena, modifications to the facility, or maintenance operations, can lead to non-compliance, which may not be immediately detected. The sometimes large number of processes, organizations, contributors and management tools can make it complex to analyse the impact of all of these non-compliances on safety. Improvements could be made in this respect. The compliance of the facility is a pre-requisite for the reliability of lines of defence and operators must consider this aspect as a priority.

2 The independence of defence in depth levels with respect to events likely to affect a facility

The independence of defence in depth levels is never total. On this basis, it is important to identify which events or failures could simultaneously affect several defence in depth levels, e.g. if a specific failure is likely to prevent the application of the planned provisions to limit the consequences of this failure, and to appraise if the action taken is sufficient. Provisions are not independent (or not) in real terms, but with respect to a given cause of failure for a given scenario. On this basis, the degree of dependence between lines of defence must be characterised in order to design and assess the safety of a facility.

While some types of dependence may be acceptable, the independence of levels of defence in depth must be targeted. From IRSN's viewpoint, defence in depth levels 3 and 4 must be as independent as possible. In fact, a core meltdown accident, should it occur, must be the outcome of one or several events combined, and the failure of the lines of defence planned to avoid meltdown at defence in depth level 3. The provisions implemented in order to limit the consequences of core meltdown accidents do not meet as demanding reliability and robustness requirements as level 3, due to the assumed lower probability of the situation occurring.

In general, the question of whether the requirements applied to level 4 defence in depth provisions are sufficient, or not, must be considered, particularly as the operating conditions of the equipment will be significantly degraded (irradiation, humidity, pressure and temperature conditions in particular) and periods of use could potentially be much longer than for lower levels. These aspects must be considered as part of future reactor development projects.

In addition, probabilistic safety studies (PSA) help to identify any failures which could simultaneously endanger several lines of defence, estimate the corresponding degree of dependence and assess the reconsideration of the graduated response planned for any given event. Such studies can particularly be used to assess the risks of common cause failure for support systems (instrumentation and control, including sensors and actuators, power sources, cooling sources, compressed air, etc.). PSA completed during the design phase for new facilities can help to revise any design decisions, if necessary, and define diversification requirements in order to limit these risks.

Hazards, particularly external hazards, are likely to simultaneously affect several levels of defence in depth, and several lines of defence at any given level, as showed by the Fukushima Daiichi NPP accident. Historically, the provisions applied at the different defence in depth levels are essentially defined based on the analysis of internal events taken into consideration in the facility safety demonstration (e.g. the failure of a component or system, possibly combined with the failure of the planned provisions against this event). Hazards are taken into consideration via design rules and assumptions for the structures, systems and components (SSC) contributing to the fundamental safety functions (e.g. physical or geographic separation, earthquake qualification). However, for SSC which are required in the event of a hazard, the same hazards are generally considered for all SCC at the design phase, regardless of the level of defence in depth applied. In other words, all of the provisions taken at the different levels of defence in depth, against natural hazards, could have been applied simultaneously if the facility's design basis risks were exceeded.

For this reason, the changes adopted in France after the Fukushima Daiichi NPP accident aimed to reinforce the provisions applied at defence in depth levels 3 and 4 for seismic risks, flooding and extreme weather conditions; these changes involve reinforcing existing provisions with a series of fixed and mobile equipment, human and organisational resources, which can be used to control the conditions of site facilities during the early days of an accident, until the off-site support services reach the site, particularly in case of extreme hazards.

The ability of sites to adapt to a wide range of situations and unexpected circumstances to be improved to complement the above provisions

The defence in depth approach is based on an ability to plan ahead for risks and limit the consequences of any situations considered as plausible. However, it is impossible to take all combinations of events and failures into consideration during the design phase, and experience feedback regularly highlights anomalies which had not been forecast, or for which the consequences had been incorrectly assessed.

The handling of events at the Fukushima Daiichi NPP, as well as at the Fukushima Daini NPP just a dozen or so kilometres to the south, demonstrated to what extent the ability of site teams to respond and adapt can prove a decisive factor when managing a totally unexpected situation.

This ability to adapt cannot be considered as a factor in the safety demonstration of a facility as such. However, it could prove indispensable when managing the wide range of actual situations which could occur and essential in unexpected circumstances.

According to research in human and social sciences, while resilience partially emerges in an emergency situation, and is indeed based on a share of creativity and improvisation, by planning ahead, the right conditions and resources to promote resilience can be identified (e.g. generic skills can be identified) and teams can be prepared to respond appropriately.

This planning process is different to the approach used for the safety demonstration, particularly due to the different purpose. The aim, in this case, is to boost the ability of site teams to respond and adapt to any given situation, potentially outside of the scope of the safety demonstration, e.g. by increasing resources or distributing them differently (shared emergency management resources). Operating procedures based on the physical state of the facility were introduced after the Three Mile Island NPP accident in the United States in 1979, and have already helped to improve the ability of operating teams to manage the wide range of actual situations which arise, and can be used to cover a long list of situations. The required actions are defined on the basis of variation in the physical parameters of the facility (levels, pressures, temperatures, flow rates, activity measurement, etc.) and not, as was previously the case, on the event identified as the cause of the incident or accident situation. In addition, if one or several systems required to fulfil the facility's safety functions fail, other, replacement, systems will be proposed. On this basis, several lines of defence are proposed and potentially implemented to handle the situation faced.

Current brainstorming policies aim to take the improvement of the operating team's resilience, and more generally the resilience of all teams at the site, a step farther, ensuring they can adapt to unexpected situations not covered by operating procedures. Other skills must be put to active use, such as expertise, but also behavioural skills, the ability to make decisions in an uncertain context, to give meaning to the current situation, even when totally unplanned, skills such as coordination, communications, cooperation, stress management and improvisation. Teams at the site must be able to take a step back and define strategies and appropriate processes in order to handle an unexpected situation in the best possible manner. To give just one example, team training must include brainstorming sessions on what solutions they could adopt in unexpected circumstances.

A resilient attitude in an emergency situation can be developed by ensuring the awareness of the limits of forward planning policies (risk analysis, rules, etc.), knowledge of vulnerable points for the facility, and an understanding of routine operations, but also via the day-to-day implementation of organisational provisions to promote the ability to respond and adapt.

Brainstorming and actions aiming to improve the resilience of the teams in charge of managing such situations are one means of improving safety and should be enhanced.

3 HOW CAN WE PLAN FOR THE RISKS INHERENT TO COMBINED MALFUNCTIONS OR EVENTS CONSIDERED AS HIGHLY IMPROBABLE?

High-risk industries in general, and the nuclear industry in particular, invest large-scale resources in defining and implementing provisions aiming to reduce the risks associated with facility operation. The situation is regularly revised to integrate new knowledge and allow for improvements, particularly with respect to situations considered as highly improbable, but which could lead to serious consequences. The appraisal of these situations is still a complex issue and no approach can totally prevent them from occurring. How can the risks incurred due to events or a combination of events considered as highly improbable, but which could have particularly serious consequences, while uncertainty increases in proportion to improbability for situations, be better understood? The Fukushima Daiichi nuclear power plant (NPP) accident demonstrated that this topic is still current in the field of nuclear energy.

This chapter gives an overview of the safety approaches implemented to date for rare accident situations with potentially serious consequences, and demonstrates how these approaches have been modified over time to better integrate experience feedback, highlighting the benefits of new knowledge for handling purposes. This chapter refers to current works focusing on the development of new methods, specifically with respect to situations which could result from natural hazards, and indicates a few potential ideas to take the appraisal of the associated risks a step further.

3 Considering rare events as part of nuclear safety

A few years prior to the Three Mile Island NPP accident in the United States in 1979, the Committee on the safety of nuclear facilities (CSNI) of the OECD Nuclear Energy Agency was already considering the limits of the approaches used at this time. The risk was then appraised based on a two-dimensional model (frequency and gravity): situations cannot be considered as acceptable if the gravity of their inherent consequences is excessive with respect to the estimated frequency of occurrence. In addition, the acceptability of the risk must be assessed, not only in terms of technical aspects, but also from a social and economic viewpoint. The aforementioned model provides the basis for the risk appraisal method still used to date, however these methods have limits, particularly due to uncertainties, which increase in proportion to the rarity of the situations considered or the gravity of their consequences, making it complex to evaluate if the provisions which could potentially be implemented to prevent or limit their consequences are reasonable.

This difficulty can only partially be overcome by the defence in depth approach, which is widely used in the nuclear safety field, and assumes that, by convention, incidents and accidents could still occur despite the preventive provisions applied, and leads to the definition of measures to mitigate the consequences of such events, if necessary. This approach has intrinsic limitations as an indefinite series of events cannot be assumed.

Stage one: combining deterministic and probabilistic approaches

With this process, by boosting the complementary nature of deterministic and probabilistic approaches - the underlying principles are briefly described below - **a wider range of events and combined events can be handled[9] over time, and above all, the knowledge of the accident scenarios which could lead to situations, which are undoubtedly rare, but must be considered as "plausible" in terms of nuclear safety, can be improved.**

With a deterministic approach, the possible consequences of a certain number of situations, resulting from unique trigger events assumed *in principle* based on plausible failures for equipment or operating errors, are examined, considering the design of the

9 Which means checking that the selected provisions were sufficient to prevent these situations or limit the inherent consequences, or, failing this, implementing new provisions.

facility or operating practices, without reconsidering the series of events which could lead to these situations. On this basis, this approach assumes that the incident or accident occurs and leads to the definition of provisions in order to keep the inherent consequences at an acceptable level. The assumed incidents and accidents are studied according to a prudent approach, i.e. in conservative conditions, with appropriate safety margins applied, some of which aim to cover uncertainties and the limits of knowledge.

The probabilistic approach is complementary and allows the risks associated with situations with combined events to be understood on a more realistic footing, considering operating experience feedback[10] and current knowledge, and allows "complementary provisions" to be defined aiming to reinforce facility safety. By developing probabilistic safety evaluations to complement deterministic studies, the level of detail of studies on the accident scenarios which could affect the facilities has been considerably enhanced, risks which the deterministic approached failed to identify are highlighted and safety is reinforced. However, results will clearly depend on the data processing methods used, and on available information and knowledge: on this basis, the evaluation of the frequencies of the different accident sequences highlighted depends strictly on available knowledge on the reliability of equipment and on potential physical and chemical phenomena; facility modelling will also affect results: e.g. simplified models are frequently used for the reactor's instrumentation and control system or human errors before or after the accident due to the inherent complexity or modelling difficulties; in the same way, reliability data is obtained straight from experience feedback, limiting the quantification of rare events.

"Practical elimination": a means of taking the prevention of situations with serious consequences a step farther

After the Chernobyl NPP accident in 1986, national and international discussions on the design and safety of new nuclear power plants planned for construction in the early 21st century led the different parties to consider that significant improvements were required in terms of safety, compared with the power plants currently in operation, or under construction, all of which had been designed prior to the Three Miles Island and Chernobyl accidents, particularly with respect to some accident scenarios including a core meltdown, which were not previously taken into consideration or were assumed to

10 Consideration of experience feedback when quantifying the reliability of equipment, consideration of assumed operator behaviour in particular.

be sufficiently improbable to the extent that additional design efforts were not necessary. A fourth defence in depth level aiming to limit the consequences of accidents with reactor core meltdown had already been introduced. However, for some situations in which a core meltdown is at least theoretically plausible, such as situations which could drive rapid, high-energy, physical phenomena, leading to the short-term failure of the containment, it did not appear possible to set up realistic provisions to mitigate the consequences. For the new reactors in question, the "practical elimination" of such situations was targeted. In this context, the term "practically" must not be understood as "nearly", but rather as "in practice".

The "practical elimination" approach is therefore mainly deterministic and aims to make serious accident situations which could lead to the early failure of the containment of radioactive products either physically impossible or, failing this, highly improbable, with a high degree of confidence, so that these situations can be considered as "excluded". This approach should only be applied for serious accident situations which cannot be covered by reasonable provisions with demonstrably limited consequences. Nonetheless, this position is not systematically applied at international level. As recent discussions have highlighted, interpretations of the approach vary, the situations to which it should be applied are defined differently, and the weighting of probabilistic input varies widely.[11]

The practical elimination of a situation can only be strictly demonstrated if the situation is physically impossible. Failing this, the designer must apply all reasonably feasible design or operating provisions to ensure that the accident situation can be considered as highly improbable with a high degree of confidence. On this basis, demanding requirements must be implemented to ensure that targets are met.

Probabilistic safety studies (PSA) are used to check that the situations to be practically eliminated are highly improbable. However, these studies should be used with caution due to the impact and sensitivity of the models used and the assumptions made for the results. If a major accident occurs, subsequent analysis frequently concludes that the probability of the event occurring had been underestimated, in both the nuclear industry and in other industries. Furthermore, is it necessary to identify situations requiring "practical elimination" at an early stage in the design phase of a nuclear reactor, and should the inherent requirements be discussed at this stage[12].

11 In some cases, if a situation is estimated as highly improbable, it may not be necessary to implement complementary preventive provisions, in addition to the existing defence-in-depth provisions.

12 "The "practical elimination" approach of accident situations for water-cooled nuclear power reactors" – IRSN, 2018. https://www.irsn.fr/practical-elimination-2018

The accident at the Fukushima Daiichi NPP: appraising natural risks

After the accident at the Fukushima Daiichi NPP, potential serious accidents which could arise due to natural risks were considered in more detail. Limitations were rapidly identified. In fact, to take into account the total loss of power and ultimate heat sink affecting all of the facilities at a nuclear site, which could occur subsequent to a more severe natural hazard than those considered to date, implies to characterize these hazards. In addition, while probabilistic safety studies in relation to seismic hazards have been developed and provided input, which has contributed to significant safety improvements, the development of these studies is hindered by limited knowledge of natural hazards and the vulnerability of the facilities with respect to these hazards.

On this basis, in order to enhance the safety of nuclear facilities, hazards with a return period well in excess of 10,000 years, i.e. hazards which have far less than one chance in 10,000 to occur each year, must be characterised, and the strength of structures and the behaviour of facility equipment must be assessed with respect to such hazards.

Nonetheless, improving knowledge of natural hazards remains a priority in order to appraise stakes and enhance the safety of facilities in terms of rare events if necessary. In recent years, new approaches aiming to better characterise highly improbable hazards have been under development.

New approaches to characterize natural hazards

Over the years, exceptional events have led to the reinforced protection of French nuclear facilities against natural hazards: extremely low temperatures affected the availability of the ultimate heat sink at the Saint-Laurent-des-Eaux NPP during the winter of 1985, a high tide combined with strong winds partially flooded the Blayais NPP in late 1999, an earthquake and tsunami struck the Fukushima Daiichi NPP in 2011. Designers and operators have reconsidered their long-standing prevailing approach based on these examples. Previously, they integrated external hazards in the design for equipment while ignoring or neglecting the effects of any combined events and all induced effects. While designers and operators attempted to demonstrate that the contribution made by external hazards to the probability of core meltdown or important releases is not decisive, the aforementioned events highlight the limits of the knowledge used.

3

On this basis, integrating external hazards in general, and potential combined events, including combinations with internal failures, as part of the deterministic approach, is still currently a concern. Work groups including experts from operators and IRSN have been set up at national level by the French nuclear safety authority (ASN) in order to define the methods used to integrate hazards and combined hazards; work groups have also been set up at international level, particularly under the aegis of the CSNI of OECD-AEN, in order to improve knowledge of natural hazards and develop evaluation methods for these hazards, and for the vulnerability of facilities to hazards which are insufficiently integrated during the design phases.

In France, one of the lessons learned from the partial flooding of the Blayais power plant was the need to consider combined phenomena, which were previously neglected, such as the combination of strong winds and tidal surge[13] as a flooding scenario for nuclear facilities located near the coast or an estuary. The 1999 flood also called into question the way the tidal surge data was collected and used in the application of statistical methods for flood risk assessment. By using unique data from reference stations, sample data included singular points (or outliers). The outliers included in a statistical series represent a difficulty for experts, as the approach used to integrate or exclude these data can lead to the overestimation or underestimation of the associated risks. After this flooding event, new approaches were developed in France in the field of nuclear safety, by EDF and IRSN, in addition to the reinforced protective provisions applied at facilities, in order to enrich the databases used to characterise flooding risks (flooding, heavy rain, etc.), by attempting to integrate data from wider geographic areas and dating back to earlier periods. Regional approaches were initially developed and could be used to expand the scope of the event data collected in order to boost available data. A historical approach based on archive studies and field inspections can also be used to find data for earlier events and, with the help of historians, interpret this data. This approach was enriched by the "Historical floods and storms" work group, which comprises a multi-disciplinary scientific community (historians, geographers, hydrologists, statisticians, etc.) and aims to share knowledge beyond the limited scope of nuclear safety. Historical and regional approaches are now combined for operational applications, to define sea levels in safety evaluations.

As part of the complementary safety assessments performed in France after the Fukushima Daiichi NPP accident[14], operators initially highlighted the margins gained

13 A tidal surge is the difference between the observed sea level and the forecast tidal level.

14 Complementary safety assessments were performed at each French nuclear facilities, at the request of the French Prime Minister, after the accident of 2011. They aimed to appraise the behaviour of these facilities in case of natural hazards over and above those considered during the design phase.

from the prudent approaches implemented when designing their facilities thanks to the application of conservative methods and the design and construction standards used. However, these margins are difficult to quantify and can vary over time, due to ageing phenomena or non-compliances, which is why safety bodies insist on the in-depth management of these non-compliances. A "hardened safety core" of provisions is currently being implemented at French nuclear facilities in order to manage the total loss of electrical supply and cooling at facilities in the event of "extreme" hazards, aiming to reinforce their ability to withstand these hazards, and such provisions will significantly improve safety at these facilities. However, determining highly improbable (but very intense) hazards using data which only covers more frequent (and less intense) hazards by statistical extrapolation will require continued efforts in order to take full advantage of regional and historical data. To date, this operational approach must be completed in the future by modelling the physical aspects of phenomena and any potential combinations, which are currently subject to research, for all natural hazards.

In terms of earthquake risks, the unusual characteristics of the recent Teil earthquake[15] in the Montélimar region highlights the difficulty of evaluating seismic risks in regions with moderate seismic activity such as France, and the need to identify any potentially active faults at the different sites in order to characterise earthquakes with very long return periods (more than thousands of years) which could affect these sites; this process is indispensable when studying rare events as the knowledge obtained by analysing historical seismic activity, the main design basis for existing facilities, only covers approximately 1000 years. Once again, regional and historical approaches can be combined to generate new data, which can prove helpful in attempting to control risks, even if uncertainty still applies.

These approaches must still be consolidated in order to fully contribute to expertise, which must be based on data which is as objective as possible, and on scientifically-validated approaches, while some developments are still mainly at the scientific research stage. The sharing of the efforts required for academic research must be encouraged in order to generate new knowledge.

The development of innovative mathematical methods must be encouraged and could confirm that the existing provisions are already sufficient, or, on the other hand, highlight that the reliability of the facilities must preferably be reinforced. Nonetheless, these methods will still come with uncertainty, regardless of the new knowledge they may bring. Their contributions must therefore meet conditions to be defined in the future prior to use for the safety demonstration.

15 Earthquake on 11 November 2019 which particularly affected the municipality of Teil.

3 Continuing development programmes to further enhance risk assessments

While experts are frequently considered as knowledgeable and expertise as a process leading to an objective result, this viewpoint must be at least taken in perspective for complex systems, particularly when focusing on rare events. Such risks are indeed evaluated on the basis of knowledge which has not been confirmed and is subject to uncertainty. Multi-party debates between stakeholders, particularly industrial firms, safety bodies, and society at large, are all driven by these uncertainties, while contributing to expertise. Any major accident will unavoidably lead to the reconsideration of the contributions and limits of the applicable policies, and encourage new, more suitable and effective, methods, if necessary. Scientific progress will also lead to regular reconsideration of the assumptions applied when designing facilities.

While analysis of experience feedback, and research and development works, have led to significant safety improvements for nuclear reactors, including those commissioned in the 1970’s, these efforts must continue and methods must still be developed in order to improve the appraisal of risks and identify cliff edge effects. Discussions between experts and researchers, at both national and international level, provide input.

4 RECOVERY AFTER A NUCLEAR ACCIDENT: AN ESSENTIALLY SOCIETAL PROCESS

Recovery after a nuclear accident is extremely complex, both for the victims and for all parties managing the rehabilitation process. This complexity is generally caused by two factors. Firstly, the radioactive contamination of a region will affect all aspects of the day-to-day lives of the local populations, and all regional public and private services. Secondly, unlike, for example, a natural catastrophe (flooding, earthquake, etc.), the radioactive contamination of a region must be considered over an extensive timescale (several decades, potentially more).

In this context, it is important to consider experience feedback from the Chernobyl and Fukushima Daiichi accidents in order to support the preparation of recovery management[16].

Recovery: a complex, multi-dimensional landscape

Recovery after a nuclear accident is complex at several levels: for the individuals and communities affected, but also for all contributors to rehabilitation management.

At individual level, the radioactive contamination of a region will substantially disturb all aspects of the day-to-day lives of the local populations over an extended

16 List of references:
- Schneider, T., Maître, M., Lochard, J., Charron, S., Lecomte, J.-F., Ando, R., Kanai, Y., Kurihara, M., Kuroda, Y., Miyazaki, M., Naito, W., Orita, M., Takamura, N., Tanigawa, K., Tsubokura, M., Yasutaka, T. The role of radiological protection experts in stakeholder involvement in the recovery phase of post-nuclear accident situations: Some lessons from the Fukushima-Daiichi NPP accident. (2019) Radioprotection, 54, pp. 259-270.
- Gariel, J.C., Rollinger, F., Schneider, T. The role of experts in post-accident recovery: lessons learnt from Chernobyl and Fukushima. (2018). Annals of the ICRP, 47 (3-4), pp. 254-259.

period, affecting their standard of living and well-being. The following types of disturbance are considered:

- apprehension towards the quality of the environment due to the radioactive contamination;
- doubt over the safety and quality of food products;
- upset family relationships due to the differing reactions to this unusual situation;
- strong apprehension towards the future, particularly that of children;
- conflictual social relations based on different lifestyle choices between neighbours and acquaintances (some wish to leave, others stay, etc.)
- significant upset in terms of education, healthcare and businesses due to the disturbance to the socio-economic system.

This situation is complex due to the many factors involved, and will oblige the victims to face a dilemma, which we could summarise with the following questions:

- For those still in the affected region: should I stay or leave?
- For those having left, voluntarily or otherwise: should I return or stay away?

Whatever the precise situation, it is easy to understand that no simple answer exists to these questions.

Over and beyond individual preferences, this situation is just as complex at community level. Social interaction will indeed be seriously disturbed, which will reduce the cohesiveness of the community. This reduction in cohesiveness could also be driven by a feeling of inequality in terms of the decisions taken by national and local authorities. To give one example, compensation systems are generally launched based on administrative borders, which can lead to two families living on either side of a border not receiving the same compensation, which would trigger conflict. Finally, economic upset will lead to major consequences, in the same way as those affecting the social system and public/private services.

Business practices can also be overturned. Jobs can be lost or adjusted, and working conditions must be adapted. Agriculture is generally the most affected segment, however other fields may have to manage the consequences of any contamination of work and production sites. Services must be restored, sometimes with adaptations. Former colleagues may not return while new workers will appear – sometimes without their families – to make up team numbers or decommission the damaged facility and reconstruct the area affected.

In general, all such disturbances help to exacerbate the distrust shown towards national authorities and institutional experts by those affected and as demonstrated in the Fukushima prefecture, some parties will turn to the local authorities, and mayors in particular. Such authorities will find themselves in a delicate position, where they must contribute to the implementation of national decisions while considering the needs and expectations of the people affected. **Conflict between decisions reached at national level and the concerns and expectations of the local communities, which may diverge or even differ, appear in real form at local level.**

What conditions are required in order to facilitate the rehabilitation for the affected populations and territories?

The main condition, which is the basis for the reconstruction process, is the possibility for the people and communities affected to be able to access reliable and easy to understand information, allowing them to plan for and evaluate the radiological situation both as individuals (i.e. for all day-to-day activities, particularly allowing people to identify their own situation with respect to that of others) **and groups** (at community level). Experts must support this phase, and as explained later, play an essential role while paying close attention to their attitude towards the populations affected. These experts must provide information on exposure to radiation, take measurements, and even support inhabitants with taking measurements and helping to interpret the results. The aim is to ensure that radioactivity, which is impossible to see, can be identified using measurements. Allowing inhabitants to appraise the radiological situation is a key factor in ensuring they can establish their own benchmarks, are able to make educated decisions for their own protection and can also assess the efficiency of the actions taken by both themselves and the public authorities.

A secondary condition required to simplify the rehabilitation process is the community's ability to respond and react to this unusual and highly destabilising situation. The aim is:

- to invent new forms of cooperation with all stakeholders (whether experts, professionals, local or national authorities, society at large, etc.) in a conflictual and distrusting context. Creating the right conditions for mutual trust is a key factor in the rehabilitation process;
- to provide inhabitants with a means of being directly involved in the radiological situation via the decision-making processes and the actions implemented by the local and national authorities to reduce the exposure faced by the populations (decontamination actions, waste storage, etc.).

4 What challenges for those involved in the rehabilitation process?

While recovery is unusually complex for the inhabitants affected, the same can be said for all contributors to the rehabilitation process. The situation is mainly complex for the latter due to the multi-faceted nature of the situation, where the actions of all contributors must be coordinated. Due to the many unique aspects of such a situation, each authority or each expert will tend to act independently, without appraising and considering all of the stakes. Radiation protection experts will tend to focus on levels, measurements, and protective actions to be prepared and deployed, without systematically considering any constraints due to other aspects which need taking into consideration. This approach can lead to situations where conflicting provisions may be applied by different decision-makers.

In this context, establishing dialogue involving all parties and covering all aspects between the authorities, experts and people affected is critical. The Fukushima Daiichi accident demonstrated that this type of dialogue is helpful.

Furthermore, it is important for experts to maintain a strictly neutral position when fulfilling their roles, and show fairness when supporting and guiding all of the populations affected, regardless of their preferences or decisions. When faced with an unwanted and unusual situation, people can react in many different ways and the expert must respect such differences. The wide range of choices made by inhabitants can lead to conflict and divisions within the communities, and external parties must tread with care to avoid exacerbating this situation by adopting viewpoints which could degrade community cohesiveness.

To summarise and in all circumstances, experts and authorities must respect the decisions made by individuals and communities.

The rehabilitation process is a societal affair

As described previously, recovery after a nuclear accident is a mainly societal process. Experience feedback from the Chernobyl and Fukushima Daiichi accidents demonstrate that the involvement of the people affected and their host communities is a key factor in rehabilitation. Establishing dialogue between all parties involved, including affected persons, is necessary for all fields covered (decontamination, waste management, lifting of restrictions and evacuation orders, restoring social and economic conditions, etc.), in order to jointly prepare the actions to be taken. Decisions must be taken jointly between all of the parties involved. In this process, the role played by local authorities, particularly mayors, is critical in order to meet the expectations of the population, which may vary, and even conflict.

The involvement of local parties will vary over time

During the recovery process, the situation will change over time (emergency, transition and long-term phases), therefore the involvement of local populations can be adapted to match the current priorities. During the emergency phase, the main concern of the authorities is to protect the health of the populations based on benchmark values. During this phase, the risk assessment and related communications and protective actions are deployed by the national and local authorities with limited dialogue due to the degree of urgency and the circumstances. From the transition phase, it is important to interact with society at large and particularly to involve inhabitants in the radiological characterisation process. This involvement is simplified by rapidly developing radiological measuring systems that are easy to use and reliable. Protective actions could be prepared and deployed via this joint characterisation process, on the basis of a shared understanding of the radiological situation. As time passes, the purpose of the actions taken will widen to include the restoration of living conditions in general, in many fields (social, economic, etc.), and the question of radiation protection will become one aspect on a list of many others. This change of direction corresponds to greater interaction between the different stakeholders.

What role do radiation protection experts play in recovery?

A factor which the Chernobyl and Fukushima Daiichi accidents have in common, is the distrust shown by those affected towards the authorities and institutional experts. This is, in part, due to the fact that, particularly for institutional experts, the population affected feel that these experts adopt a knowledgeable approach, and provide information from a "top-down" mind-set, without considering the expectations of the population and ignoring their vulnerable circumstances. This partially explains the use of experts, often from an academic background, selected by the local authorities, or non-institutional individuals making a personal commitment. These experts are generally considered as operating independently to the authorities and the nuclear segment, and more prepared to listen to the concerns of inhabitants. We can reach a few conclusions on dialogue focusing on radiological risks based on the statements of several of these Japanese experts. It would thus appear that:

- the purpose of this dialogue must not be to reassure inhabitants in the world of uncertainty involved in exposure to low doses;
- this dialogue must maintain the mind-set behind scientific knowledge and be managed with humility, integrating uncertainties and the limits to current knowledge;
- the vulnerable circumstances of the people affected in a totally novel situation must be taken into consideration.

It is also important for experts to support the local initiatives of inhabitants and communities, particularly those aiming to better understand and evaluate the radiological situation. Experts must listen to inhabitants in order to respect their approaches and viewpoints and work with them in the field. Experts must attempt to provide at least partial answers to the questions and concerns of the individuals affected and help to share knowledge with the latter. This approach will boost the expertise of local parties and hence their ability to take action themselves. Promoting initiatives such as radiological measurement campaigns or testing radioactivity in local food can contribute to this trend.

In addition, the conclusion was reached that radiation protection experts must ensure that they never work alone in their own field of expertise, and systematically cooperate with experts from other fields (health, food safety, socio-economic parties, etc.). This holistic approach will help to avoid actions with contradictory effects.

Reconciling experts and those affected: the joint expertise process

Past experience from Chernobyl and Fukushima Daiichi has proven that launching a joint expertise process is one means, among others, that radiation protection experts can use to open up long-lasting dialogue with the individuals and communities affected.

The aim of the joint expertise process is to involve stakeholders, including the inhabitants affected, in the recovery in order to improve radiological protection by developing a radiation protection culture and by restoring their living conditions.

Several phases can be identified when deploying this process:

- establishing dialogue by identifying the difficulties and challenges faced by the population;
- involving those affected in radioactivity measurements in order to provide them with the means of evaluating their exposure and establishing their own benchmarks, particularly by comparing their exposure with that of others, within the community and elsewhere;
- identifying protective actions, including self-protection, and implementing these actions after the characterisation of the radiological situation;
- finally, organising citizen monitoring processes and implementing local projects aiming to restore sustainable living conditions at community level via social and economic actions.

Prior to launching this joint expertise process, easy-to-use radioactivity measuring equipment must be provided to individuals. Thanks to current technologies, such equipment is relatively easy to deploy.

Experts must be involved in recovery at local level based on ethical principles

In a context where the people affected are extremely vulnerable due to the serious disturbance to all of their benchmarks in their daily lives, experts supporting these individuals must ensure that their actions are guided by ethical principles. The main principle is to ensure that the independence, freedom of choice and freedom of decision of the people and communities affected are maintained. In practice, this means that:

- inhabitants must be voluntarily involved;
- experts must provide transparent communication, and insist on what is actually known from a scientific viewpoint, and what must still be determined;
- experts must avoiding judging individual choices and decisions, and support all individuals affected without exception;
- experts must be able to report on their words and acts at any time.

4 Dialogue, independence and shared expertise

Past experience gained in the wake of the Chernobyl and Fukushima Daiichi nuclear accidents demonstrated the complexity of recovery and the wide range of factors involved, which significantly disturb individuals and communities.

The first lesson learned is the importance of involving all stakeholders in the evaluation process and when managing these situations, but also in upstream preparation. Radiation protection is not the only priority, sustainable living conditions must be restored for the people affected. However, in these situations, society at large ceases to trust institutional – political, administrative or technical – bodies. On this basis, it appears indispensable for all stakeholders to cooperate as closely as possible – national and local authorities, experts in various disciplines, whether institutional or other, society at large and economic contributors, etc. – in establishing and deploying an open and transparent rehabilitation process.

In these situations, many problems are handled at local level, and radiation protection experts must primarily target this level, and comply with ethical principles. By listening and showing respect for each individual's choices, experts can help to meet the expectations and concerns of both individuals and communities, simplify initiatives aiming to measure radioactivity and give it real form, via joint expertise processes, and promote the emergence of a practical radiation protection culture allowing local parties to recover a certain degree of independence and make more informed decisions. If we combine these conclusions, it appears that, the question is not to determine if those affected trust the experts, but whether the experts trust the initiatives of the people and communities affected.

At the end of the day, the rehabilitation process will depend on the stakeholders' ability to think and act jointly, leading to far stronger results than they could achieve as individuals.

5 POPULATIONS AFTER THE EVACUATION

One potential protective action which can be implemented in the event of a nuclear accident is the evacuation of populations in order to avoid their exposure to radioactive releases and therefore radioactivity. Such evacuation policies can be decided by the authorities, either preventively (i.e. before the releases start), or after releases and the characterisation of the radiological situation of the environment. In addition, as observed during the Fukushima Daiichi accident in 2011, inhabitants in the area affected by potential or actual releases can decide to leave their homes and remain at a distance from the region by their own choice ("self-evacuation").

Approximately 300,000 individuals were evacuated from the area around the Fukushima Daiichi nuclear power plant, half when ordered by the authorities, and the other half at their own initiative (sometimes at the recommendation of the authorities). Although evacuation may be necessary, it is not a simple task, particularly in emergency conditions and in the context of the damage caused by the earthquake and the tsunami. Evacuation will unavoidably cause damage, particularly for vulnerable and dependant individuals. After setting up a post-accident zone (SDA for "Special Decontamination Area"), approximately 150,000 people were rehoused by the authorities pending the lifting of the evacuation orders.

Almost ten years after the accident, it is estimated that less than 20,000 people have returned to their homes. Almost 24,000 inhabitants will probably never return home as their houses are located in a "difficult-to-return" zone, which is strongly contaminated and which, to date, has only been punctually decontaminated. The low numbers of people returning reflects the difficulties inherent to the long-term management of the consequences of significant regional contamination[17].

17 List of references:
- Croüail, P., Schneider, T., Gariel, J.-C., Tsubokura, M., Naito, W., Orita, M., Takamura, N. *Analysis of the modalities of return of populations to the contaminated territories following the accident at the Fukushima power plant* (2020) Radioprotection, 55, pp. 79-93.

5 Evacuation: a protective action which is delicate to implement and has inherent risks

Experience feedback from the Fukushima Daiichi nuclear power plant (NPP) accident demonstrates the complexity of evacuations. The Japanese accident highlighted several key points to be taken into consideration when implementing such action. The nuclear accident itself was the consequence of two natural catastrophes (earthquake, tsunami), which rendered the management of the accident itself even more complex.

- Preparation by authorities and the population is critical to limit the need for improvisation. Due to the timeline of orders, the wide range of details (e.g. an evacuation was recommended in some areas and mandatory in others), the step-by-step process (particularly repeated evacuation steps when the first gathering sites were found to be in a contaminated area), the lack of clear information on the duration of the evacuation and its end date, the definition of evacuation zones and variation in these zones over time, the populations affected were left with the impression that the authorities were improvising and increasingly distrusted the former. It is essential to insist on the importance of managing regular exercises in order to improve the preparation of both public services and populations.

- Selecting the appropriate location for gathering areas for evacuees is essential and it must be possible to adapt locations to the immediate conditions. It will never be possible to predict contamination areas and several options must be pre-determined in order to allow evacuees to gather in safe places, unlikely to be affected by contamination. As shown by several examples, during the Fukushima Daiichi NPP accident, populations had been gathered in zones with higher contamination levels than the areas they had left, requiring a second evacuation process.

- Finally, the evacuation of vulnerable and dependent persons and the institutions that receive them is a central issue and specific preparation and planning is required. We could mention the example of the retirement home in the village of Iltate in Japan which was not evacuated, based on a decision by the mayor, despite the instructions issued by authorities. This decision led to a lower level of fatalities in this institution than in other similar institutions that were evacuated.

Evacuation and rehousing have significant effects on the living conditions and health of the people affected

After the evacuation process, the inhabitants were housed in temporary dwellings. Despite the efforts of municipalities, this rehousing policy had a hard-hitting effect on the cohesiveness of the local communities. While the elderly stayed in temporary housing, most families opted to purchase or rent accommodation elsewhere in Japan. Several years after the evacuation, it is apparent that most of the occupants of temporary dwellings are aged over 70, while the younger generations have resettled elsewhere. In addition to hampering the cohesiveness of the community, this situation also separated families and led to a feeling of isolation for the older generations. The compensation system applied may also have aggravated this loss of cohesiveness. The compensation system was indeed based on the post-accident radiological zones defined, which may have led families living close to each other to receive different levels of compensation, ranging from a factor of 1 to 10. This led to feelings of injustice and unfairness, breaking up social relations and creating cleavages.

These evacuation and rehousing conditions generally and obviously affected the health of those displaced. While the levels of internal or external exposure to radioactivity faced by the population remained relatively low, leading to health effects which will be difficult to quantify, the same cannot be said for the indirect consequences of the evacuation and those attributable to changing living conditions.

Several studies have demonstrated that the Fukushima Daiichi NPP accident led to approximately 2,000 “indirect” fatalities (i.e. not related to exposure to ionising radiation), particularly in the most vulnerable populations (the elderly, ill, etc.).

In addition, due to the deterioration in their living conditions due to the evacuation, health effects not related to exposure to ionising radiation were observed in groups of evacuated inhabitants. Such health effects included diabetes, or a negative trend in indicators such as BMI, blood pressure or cholesterol, etc. This type of health effect was also observed for people who were not evacuated, but lived near to the areas with the highest contamination levels due to stress after changes in their environment.

5

After lifting the evacuation orders: the tough decision between returning or staying away

After the evacuation orders were lifted, each individual had to make the difficult decision of whether to return or stay away, which combined with the radiological criteria defined by the authorities and the deployment of actions to ensure these criteria were met, dictated return dynamics.

Between July 2012 and August 2013, post-accident zones were set up gradually in the areas with the highest contamination levels. Three zones were defined based on radiological criteria:

- a "green zone" where evacuation orders were ready to be lifted when an external annual dose of less than 20 mSv/year was reached;
- an "orange zone" considered as the "Restricted Residence Zone" where only businesses were authorised, or homes could only be occupied during the day. This zone corresponded to exposure of between 20 and 50 mSv/year;
- finally, a red "difficult-to-return" zone, where inhabitants will not be able to return before a long period. The annual dose in this zone exceeded 50 mSv/year.

Decontamination operations were organised in the green and orange zones, as early as 2013, to allow people to return home, while the authorities defined three criteria for the lifting of evacuation orders in each municipality:

1| the completion of decontamination operations throughout the municipality (operations organised by the State), until the individual dose falls below 20 mSv per year;
2| the rehabilitation or reconstruction of infrastructures (water, gas, electricity, health centres, shops, administrative services, schools, etc.);
3| coordination with all inhabitants.

In practice, lifting evacuation orders proved to be a lengthy and complex process. Orders were lifted in stages due to the varying periods required to meet all three criteria in each municipality. Within the populations affected, each individual, depending on their location, needed to face the critical question of whether they should stay or leave, or if they were evacuated, whether they should return to the areas or stay away. This tough decision depends on a long list of factors, in particular: belief in radiological protection for yourself and your family, in a context of uncertainty and controversies, the provision of accommodation (the old or new accommodation), the restoration of infrastructures (services, networks, etc.), the continued existence of a job (the old or a new job, possibly with adapted working conditions), conditions for children (school, day nursery) - as the protection of children is a priority factor -, the restructuring of social activities within communities while neighbours or other relations may have changed, and the continuation of recreational and cultural activities.

The decision reached by each individual must be informed, respected and supported. Nonetheless, the wide range of preferences may have led to conflict within families or communities, reducing cohesiveness. Such conflict hampered the preparation of joint development projects at local level.

The completion of decontamination operations depends on achieving a set target in terms of the exposure of inhabitants (below 20 mSv/year). To begin with, the authorities defined the corresponding dose rate for this purpose, i.e. 3.8 µSv/h depending on the selected scenario. This level was particularly disputed by parents, who considered that it was inappropriate to use a criterion generally applied to workers for their children. Consequently, the authorities reduced this level to 0.23 µSv/h, corresponding to an additional 1 mSv/year. The matter of thresholds notably led parents to limit the outdoor activities of their children. The lack of exercise helped to increase obesity in young people in the Fukushima region.

In addition, decontamination operations generated a substantial volume of waste, which was stored in the municipalities for many years. These storage sites created an eye sore and could act as a source of re-contamination (e.g. in case of heavy rain), and also discouraged people from returning to the area.

Ten years later, few people have returned

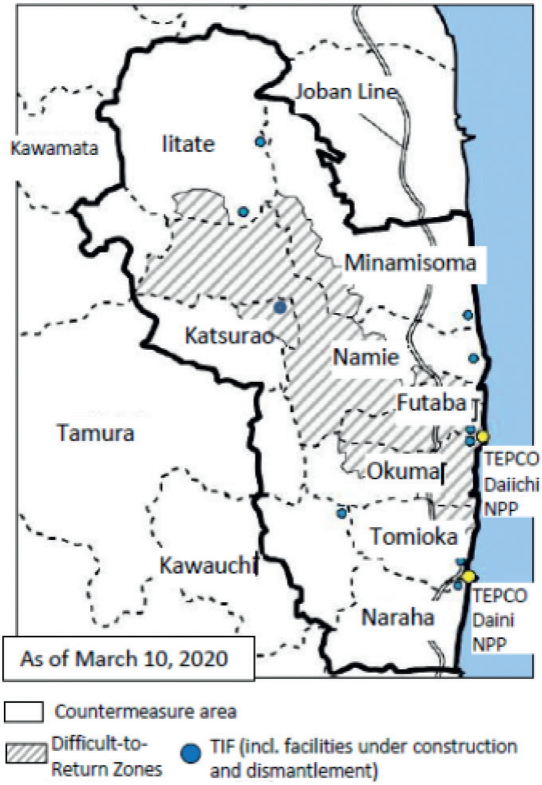
In general, few people have returned to the decontaminated parts of the SDA a decade later. Table 1 (see also figure 1) provides an overview of the situation at end-2020 and shows that approximately 20% of inhabitants have returned to the twelve municipalities considered on average. It is apparent that the date on which the evacuation order is lifted correlates with the return rate: the later the order is lifted, the lower the return rate.

We could mention the town of Naraha as an example of the low return rate. In Naraha, the evacuation order was lifted in 2015 and, at that time, according to a survey carried out by the reconstruction agency, less than 50% of the population was considering a rapid return, 25% were uncertain and the last 25% did not intend to return. One year later, less than 10% of inhabitants had returned and a total of 25% had returned the following year. It was only in 2017 that Naraha population levels returned to approximately 50% of the initial level. This difference observed between theoretical intentions and how many inhabitants actually return reflects the difficulty faced by the latter in reaching a decision in a context dominated by great uncertainty, in terms of the appraisal of both radiological risk and living conditions, combined with apprehension of the degree of restoration of infrastructures. In this respect, according to a survey carried out by Fukushima University in 2012, evacuees mentioned the radiological situation as their main concern. However, three years later, the same survey indicated that the decision to not return to the original municipality was dictated by living conditions rather than the radiological situation.

Table 1: Population variation between 2011 and 2020 in municipalities having received an evacuation order.

Municipality	Date on which the evacuation order was lifted	Status of the lifting of the evacuation order	No. of people registered as residents in March 2011	No. of permanent residents in Dec. 2020	Return rate in Dec. 2020	Source
Hirono	Sept. 2011	Total	5,490	4,216	77%	https://www.town.hirono.fukushima.jp/index.html
Tamura Miyakoji	April 2014	Total	380	214	56%	http://www.city.tamura.lg.jp/soshiki/8/hinanzyoukyou.html
Kawauchi	Oct. 2014	Partial	3,038	2,523	83%	http://www.kawauchimura.jp/page/dir000112.html
Naraha	Sept. 2015	Total	8,011	4,038	50%	https://www.town.naraha.lg.jp/admin/cat337/006099.html
Katsurao	June 2016	Partial	1,567	327	21%	https://www.katsurao.org/life/4/20/65/
Minamisoma Odaka	July 2016	Partial	12,842	4,293	33%	https://www.city.minamisoma.lg.jp/portal/admin/tokeijoho/5307.html
Kawamata Yamakiya	March 2017	Total	1,259	343	27%	https://www.town.kawamata.lg.jp/site/sinsai-saigai/yamakiyatikukyojyuujyoukyou.html
Iitate	March 2017	Partial	6,509	1,482	23%	http://www.vill.iitate.fukushima.jp/soshiki/2/424.html
Namie	March 2017	Very limited	21,434	1,554	7%	https://www.town.namie.fukushima.jp/
Tomioka	April 2017	Partial	15,960	1,568	10%	https://www.tomioka-town.jp/saigai_fukko/2201.html
Okuma	April 2019	Very limited	11,505	283	2%	https://www.town.okuma.fukushima.jp/soshiki/jumin/1007.html
Futaba	Zone 3		7,140	0	0%	https://www.town.fukushima-futaba.lg.jp/5873.htm
Total			**~ 95,000**	**~ 21,000**	**22%**	

Figure 1: Map showing the area evacuated (SDA: Special Decontamination Area, black line) and the municipalities affected (see table 1). The hatched area is the "difficult-to-return" zone.



Evacuation and return of the population: What lessons can be learned from the Fukushima Daiichi NPP accident?

Conclusions reached based on the evacuation after the Fukushima Daiichi NPP accident must be weighted by the fact that this was a secondary event coming after a major earthquake and tsunami. Evacuation operations were therefore complicated by the fact that many infrastructures (roads, power grid) had been destroyed, which added chaos to chaos.

5

The basic principle underlying an evacuation operation is to avoid aggravating the situation by making inappropriate decisions. In order to achieve this target, it is necessary to plan for which sites must be evacuated or not, how long will these evacuations take and consider the drawbacks/benefits ratio for health establishments (hospitals, retirement homes, etc.) and any industrial facilities which cannot be easily shut down. Various scenarios must be considered, ranging from temporary evacuation (a few days to a few weeks) to long-term evacuation (several months or even years). The temporary rehousing of several hundred to several thousand individuals must be planned in advance. Alternatives to evacuation, such as extended shelter, must also be considered as part of management plans. According to conclusions from the Fukushima Daiichi NPP accident, close attention must be paid to living conditions during the rehousing period, particularly in terms of monitoring health and maintaining the cohesiveness of the evacuated community.

As demonstrated by the low numbers of returning populations, it is important to remain transparent from the evacuation phase: the authorities must clearly indicate the criteria underlying the declaration to evacuate. Secondly, it is essential to involve the stakeholders (including inhabitants), as far as possible in a context facing high levels of uncertainty, in the processes to be prepared in view of lifting evacuation orders and authorising people to return. With this in mind, these processes must be prepared, particularly in terms of the flexible criteria to be applied when lifting evacuation orders. In particular, the use of radiological criteria, *i.e.* inflexible numerical values, demonstrated its limits in a context with high uncertainty, in the context of the Fukushima Daiichi NPP accident: the binary approach (good below, bad above) was sometimes unsettling, and even led to discrimination. Finally, it clearly appears that the return of evacuees to the decontaminated areas is a personal decision and must be made possible while respecting the independence of the evacuees and maintaining decent living conditions, for both voluntary and mandatory evacuations.

According to the example of the Fukushima prefecture, ten years later, it will still take many years to reconstruct and breathe new life into the regions affected, as the municipalities have difficulty planning for the future and sizing their infrastructures due to the low numbers of returning inhabitants. The decision to return to the area must be reached by each family and each individual affected based on their preferences and choices. To date, the municipalities are redirecting their activities, particularly economic activities, while opting for innovative approaches. The aim is to both increase appeal for former residents and attract new inhabitants. On this basis, municipalities must be able to constantly adapt in order to be able to match the widely-ranging choices made by the inhabitants affected by the consequences of the accident. In the coming years, the profiles of inhabitants are expected to change and some will be new arrivals having decided to take advantage of the opportunities offered by the revitalization plans, primarily economic, implemented by local and national authorities.

When managing the populations affected returning to the area or new arrivals in regions previously affected by a nuclear accident, it is also important to consider the monitoring of long-term health effects. Inhabitants raise multiple queries in this respect. Over and beyond concerns relating to the safety of the damaged facility (is the facility really safe and could a new accident occur?), inhabitants are facing a long list of questions: are waste storage sites safe, could they contaminate the environment? What is the real level of exposure of the population? Is there any risk of transfer of contamination from nearby non-decontaminated areas to already decontaminated surfaces? All of these questions are legitimate and answers must be provided as part of a structured dialogue involving the population, authorities and experts. The role played by the latter is critical. It is obvious that very few of them have received the necessary training and preparation to manage this type of situation. According to observations in Japan, the role of supporting and listening to the concerns of the people returning to the contaminated areas was, in most cases, played by experts from an academic background or non-governmental bodies, rather than the institutional bodies in charge of radiation protection.

The difficulties inherent to the long-term management of the consequences of significant regional contamination

After the accident at the Fukushima Daiichi NPP, the authorities decided to "reconquer" the contaminated areas, evacuated as part of a massive decontamination campaign. How this type of situation is managed must be considered based on the analysis of populations returning to the area, characterised by a low return rate after the evacuation orders were lifted. Radiological, as well as socio-economic aspects, needed to be taken into consideration while respecting individual and group decisions. Timescales play a key role in this context, from various viewpoints:

- during the evacuation, it appeared necessary to plan ahead, as far as possible, for subsequent stages, and particularly the decision-making processes which would lead to the potential return of inhabitants. It is not easy to forecast future changes in the situation, however the outcome of the Fukushima Daiichi NPP accident demonstrates that it is helpful to prepare, particularly in terms of the future selected radiological criteria, and focusing on their variation over time;

- decisions regarding change in post-accident zones and lifting of evacuation orders must be reached jointly and discussed with all stakeholders (clearly including inhabitants) as they must integrate many factors ranging well beyond radiological issues.

The analysis of the management of the return of populations also highlighted the key role played by the support mechanisms provided for populations, both during the evacuation period and when planning for people to return to the municipalities affected. An ideal, totally fair, compensation system is most probably impossible to achieve, however it is essential to consider any compensation frameworks and post-nuclear accident socio-economic booster plans during the preparation phase. In addition to compensation, these mechanisms relate to housing benefits, the development of infrastructures and support for pre-existing or new economic activities, and the implementation of environmental and health monitoring programmes covering the populations having decided to return to these areas. The evacuated residents, who decided to stay away from the regions affected, must also be monitored and supported. It is complex to decide on the format of these mechanisms, which play a key role both in guaranteeing decent living and working conditions for the people affected by the accident and in allowing them to make an informed decision for their future.

After a nuclear accident, it is also essential to set up a monitoring programme for environmental contamination, as was the case in Japan. The long-term future and contribution of such a programme to the organisation of a monitoring programme must be planned for. The role of radiation protection culture and passing this culture on to the younger generations must also be examined and planned for as the memories of the accident and its consequences will tend to fade with time. In the same way, the monitoring of changes in the health of the populations living in the municipalities where the evacuation orders have been lifted must be reviewed. To what extent will the structures set up meet the expectations of these populations and is the health monitoring programme set up suitable to meet the challenges inherent in life in these regions?

Finally, according to the analysis of the conditions in which populations return to the area, the ability to restore healthy socio-economic conditions in the municipalities after the lifting of evacuation orders is a key factor. Each municipality is a special case due to local particularities, the scale of contamination, the activities affected, the structure of the population having decided to return, etc. In some municipalities, medium- and long-term socio-economic dynamics will sometimes depend on the agricultural situation, the ability to attract new inhabitants, environmental management guarantees or the launch of a common development project at regional level. In this context, it is essential to consider the role to be played by radiation protection in more depth, as such protection is only one of the facets of the aspects to be taken into consideration to guarantee decent living and working conditions and support socio-economic development projects while respecting the decisions of individuals and local communities.

6 EMERGENCY EXERCISES, LIMITS AND OPPORTUNITIES

Emergency exercises help improve the resilience of organizations and the emergency management system as a whole. Nonetheless, how can the factors identified as essential for effective emergency management be leveraged via exercises and how can they be adapted in preparation for unexpected situations?

Exercises, a key factor in improving the response of an organization in the event of an emergency...

The ability of an organization, more generally a State, to manage an emergency situation or a major nuclear or radiological crisis depends on its ability to mobilize a large number of parties and effectively coordinate their actions. The roles and responsibilities of each party must be clearly defined for the purposes of effective coordination, not to mention interfaces, good mutual awareness, compliance with pre-defined lines of communication, etc.

Actions, technical expertise, decision-making and communications must all be coordinated as a key part of emergency management. In order to improve the overall abilities of an organization or a State, exercises must be organised aiming to test a varying list of components underlying a response force and how these components interact.

For technical experts, exercises provide a means of practising technical evaluations within periods compatible with decision-making requirements, testing inter-expert communications, and their ability to meet the requirements of authorities or the media. On this basis, these exercises can be used to assess their level of preparation.

6 …However significant intrinsic limits remain

Exercises incorporate significant intrinsic limits. They generally correspond to specific and known accidents, rare but identified. Several types of exercises exist, with different objectives, contributing parties and formats. National exercises operate at a larger scale to other exercises. These exercises mobilize a limited number of parties (Prefectures, operators, safety authorities, experts in radiological risks) and the respective responsibilities are defined in texts (emergency plans, circulars, etc.). Although this number of participants is limited by actual conditions, it does constrain the technical scenario, which must allow all parties to participate.

Contributors to technical expertise are required to perform many tasks, such as implement the different resources, for example a crisis centre used to investigate the situation, use mobile equipment to deploy measuring strategies and apply analysis methods, particularly for modelling purposes. While crisis centres are regularly set up by experts during exercises, in the field deployment - particularly the measuring of radioactivity in the environment, an essential task in order to determine the actual situation for an event - are less frequent as the exercise scenarios and durations are not always compatible with the organisation of role play in the field.

The duration of the exercises, generally limited to a dozen hours, is also limiting. Some recent events, particularly the Lubrizol fire near Rouen in 2019, have highlighted the full difficulty of investigating a situation, and therefore planning and reaching decisions in situations with extreme uncertainty, setting a suitable tone in communications on expert subjects such as identifying releases, all over a period covering several days.

Emergency exercises, as organised today, i.e. mainly focused on a combination of expertise and decision-making, are clearly not sufficient to cover the full complexity of the subject. However, these exercises offer opportunities for role play, which help to approach events, of different types to those covered during the exercises, more effectively.

Exercises, sources of resilience

Despite all the inherent limits, exercises have one essential virtue for all participants. Particularly in the eyes of experts, exercises allow all parties to establish their own benchmarks, to assimilate the geographic scope and timescale covered by the emergency, and to test the preparation and solidarity of team members, but also

how they interact with decision-makers. To summarise, the aim is to acquire reflexes and benchmarks which will allow the experts to focus on new aspects on the day an accident occurs, boosting efficiency.

During the exercise, the experts will repeat their procedures using technical tools and working methods, an indispensable step on the path to progress. Even if modifying scenarios during emergency exercises is no easy feat, the aim is to securely anchor basic emergency management skills in organizations, ensuring a smoother ride in an actual radiological emergency situation. The aim is indeed to ensure that the experts, subject to the inherent limits of these exercises, acquire the most detailed possible understanding of their roles and the overall functioning of the emergency response structure, to promote conditions which allow them to step away from pre-defined response procedures and routines in the event of a new emergency situation, not rehearsed in previous exercises.

The traditional technical scenario includes a rapid series of events and failures, which fit in the short time period allocated to the exercise, leaving the experts and other contributors in general with little room for manoeuvre. When faced with a legitimately high workload due to the demands of decision-makers on experts from the threat phase, experts must be able to adopt a position despite uncertainty. On this basis, these exercises place experts in situations where responsiveness and forward planning are essential, with reference to the criteria used to establish an order of priority for the required investigations. In this case, the aim is to train contributors to plan ahead, establish an order of priority and reach decisions in situations with high uncertainties.

Despite the many limits, exercises help improve the professional response of regular participants. Thanks to exercises, participants, and particularly experts, can capitalize on the experience acquired during these exercises to boost resilience when faced with an unexpected situation, either individually or collectively.

Lessons learned from the Fukushima Daiichi NPP accident in terms of emergency management

The accident at the Fukushima Daiichi NPP highlighted the fundamental role played by people and organizations in limiting the consequences of the accident if the provisions and equipment set up at the facilities fail. In general, this accident led to greater awareness of the need to reinforce the resilience of organizations in order to manage combined events, which, even if they are considered as highly improbable, can occur. The resilience of the teams involved in managing the situation at the facility itself must be improved, however this is also true for all contributors in general, particularly experts as part of the decision-making process.

On this basis, the preparation of experts is part of the more general changes defined by public authorities. After the accident at the Fukushima Daiichi NPP, plans were developed aiming to boost the responses of States for several European countries, for example, the national response plan to a major nuclear or radiological accident in France and its adaptations in Defence Zones from 2014, or the Radiation Protection Act in Germany in 2017.

Based on works by the associations of European safety authorities (WENRA) and radiation protection authorities (HERCA) on extending the planning zones around nuclear facilities, States updated their planning (extension of specific response plans (PPI) in France in 2016, in Germany from 2014) and extended their stable iodine pre-distribution zones.

Post-accident strategies are defined or improved to integrate the lessons learned from the Fukushima Daiichi NPP accident and are progressively implemented and tested during exercises or workshops. To give just one example, in 2016, France organised an initial exercise at governmental level (SECNUC) which was used to test the national response plan.

The media is generally allowed to participate with, for example, in France, media pressure simulated in most national exercises, affecting all participants, particularly decision-makers, but also experts. The simulation of social networks is also becoming more widespread.

The involvement of States in the efforts of the International Atomic Energy Agency (IAEA) aiming to propose an emergency coordination mechanism, mainly based on shared assessment methods, and, at European level, the global coordination policy proposed by HERCA and WENRA in the event of a serious accident in Europe, has led to the development and execution of many international exercises.

On this basis, the CONVEX exercises organized by the IAEA aim to improve exchanges and the sharing of technical expertise as part of the application of the Convention on early notification of a nuclear accident and the Convention on assistance in the case of a nuclear accident or a radiological emergency. European exercises are also organised as workshops by HERCA or as part of research projects (FASTNET project - FAST Nuclear Emergency Tools). Finally, initiatives are launched to reinforce coordination between border countries and create networks of technical safety organisations (TSO) which can be leveraged in the event of a crisis, such as the ETSON Crisis club.

Exercises aiming to take things a step further…

Greater realism

Despite their limitations, national emergency exercises allow the parties directly involved in managing nuclear or radiological emergencies to regularly practice approaches, ensuring progressive improvements. The execution of exercises highlights certain difficulties, which would certainly arise in an actual emergency, in terms of coordination, investigation, decision-making and communications processes.

In order to improve the technical realism of exercises, the content should be permanently upgraded to integrate experience feedback from real emergencies.

Future developments could therefore take the form of a wider range of technical role play scenarios, directly inspired from the Fukushima Daiichi NPP accident (leaking fuel pools, accident involving several reactors at the same site, natural event) or more generally in relation to events which were rarely considered to date, such as multi-site situations or scenarios including errors or persistent technical inconsistencies.

From a more general viewpoint, simulating the questioning of experts by the media or by the public at large, challenging institutional expertise on the basis of their own questions or analyses, is certainly a factor which would improve the realism of the exercise.

Exercises with international participants must be encouraged. Experts contacting experts in other countries, as occurred during the Fukushima Daiichi NPP accident, would enhance the realism of handing a major nuclear emergency, with international implications. Exercises involving nuclear facilities located close to a border must more systematically include a cross-border component, at State level, involving their respective experts required to share their data and compare their expertise.

Extra unexpected factors

In order to reinforce the adaptation and improvisation skills of experts, the exercises or role play sessions organised are starting to include a greater percentage of unexpected factors, e.g. using an unknown date for the exercise, or an unknown duration (which may well exceed the usual 8 hours) or deliberately organising a lengthy session as preparation for a long-lasting situation; or simulating a situation which is not directly mentioned in a plan.

Exercises must also be improved in terms of degraded operation. Experts must be trained to be able to provide answers in different contexts, including disturbances such as a concomitant cyber-attack, combined with other crisis, if the operator fails to comply or by adapting to the new host organisations of their contacts. Exercises including other situations, such as a natural catastrophe or deliberate misconduct, must also be prepared.

Fields to be extended

The Fukushima Daiichi NPP accident demonstrated the importance of covering previously under-tested fields in exercises. Suitable exercises must be prepared.

This is particularly true for the post-accident management of a situation having led to large-scale radioactive contamination of the environment. These situations are complex to handle and involve many different parties, including some less involved during the emergency phases such as decision makers, the population or associations, therefore many queries will arise.

For the purposes of the technical evaluation and to answer these queries, new types of practice must be thought up, particularly in interaction with these parties. Field training for those specializing in environmental radioactivity measurements is another area to be expanded, both for emergency situations and for recovery management. The elaboration of dedicated, highly organized and structured exercises, of long duration and on a large scale, would make it possible to implement specific means of field expertise, such as aerial mapping which played a major role in obtaining an overview of the areas with the highest contamination levels during the accident at the Fukushima Daiichi NPP.

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Cover illustration: Visit to the Fukushima Daiichi nuclear power plant in Japan by members of the International Atomic Energy Agency (IAEA) on May 27, 2011. View of reactor No. 3. © IAEA Imagebank.

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