3.13 Technological risk: nuclear accidents

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3.13.1 Introduction

Nuclear accidents, if their consequences are not mitigated, have the potential to initiate a disaster both in the vicinity of and even far away from the damaged nuclear facility. Safety principles, safety objectives and safety rules are internationally promoted and harmonised to reduce such risks as far as possible, but there is always a residual risk, as demonstrated by the recent Fukushima Dai-ichi accident.
This subchapter presents some of the fundamental principles applied in nuclear safety. These fundamentals are introduced with the idea that they can be transposed to other technological or natural risks. It then summarises some important lessons from the three accidents that influenced the nuclear industry significantly: Three Mile Island (1979), Chernobyl (1986) and Fukushima Dai-ichi (2011).

The subchapter then explains risk assessment methodologies and describes the current efforts for risk reduction, from plant design to emergency plans.

Nuclear accidents have the potential to initiate a disaster both in the vicinity of and even far away from the damaged nuclear facility.

In conclusion, this subchapter proposes some perspectives on research that can support risk assessment or help in accident management in this area. Understanding the interactions between nuclear facilities and their environment appears to be a crucial and transversal issue.

3.13.2 Nuclear safety framework

In European Member States, Council Directive 2014/87/Euratom of 8 July 2014 (EU, 2014) provides a general framework to be applied in relation to nuclear safety. This framework is consistent with the Safety Fundamentals established by the International Atomic Energy Agency (IAEA) (IAEA, 2006), and the main recommendations provided by the Western European Nuclear Regulators Association (directive for reactors in operation (WENRA, 2014) and new reactors (RHWG, 2013)).

Some important issues are summarised below.

The IAEA (2006) has defined one fundamental safety objective, namely to protect people and the environment from harmful effects of ionising radiation, and 10 fundamental safety principles:

1. The primary responsibility for safety must rest with the person or organisation responsible for the facilities and activities that give rise to radiation risks.

2. An effective legal and governmental framework for safety, including an independent regulatory body, must be established and sustained.

3. Effective leadership and management for safety must be established and sustained in organisations concerned with, and facilities and activities that give rise to, radiation risks.

4. Facilities and activities that give rise to radiation risks must yield an overall benefit.

5. Protection must be optimised to provide the highest level of safety that can reasonably be achieved.

6. Measures for controlling radiation risks must ensure that no individual bears an unacceptable risk of harm.

7. People and the environment, present and future, must be protected against radiation risks.

8. All practical efforts must be made to prevent and mitigate nuclear or radiation accidents.

9. Arrangements must be made for emergency preparedness for and response to nuclear or radiation incidents.

10. Actions to reduce existing or unregulated radiation risks must be justified and optimised.

Those safety fundamentals are then expressed in more technical requirements or concepts in each country or at European level (EU, 2014) or in the IAEA Safety Standards.

Some important concepts are summarised below. They can obviously be transposed to other risks induced by human activities.

Safety principles, safety objectives and safety rules are internationally promoted and harmonised to reduce nuclear risks as far as possible.

The safety culture shall be encouraged by the management, at all levels in the licensee organisations: this shall include ensuring that their actions discourage complacency and encourage an open reporting culture as well as a questioning and learning attitude with a readiness to challenge acts or conditions adverse to safety (see WENRA, 2014, for example).

The defence-in-depth approach (INSAG, 1996; IAEA, 2016) is considered a key concept by which to reach an appropriate level of protection from nuclear risk. For example, Council directive 2014/87/Euratom (EU, 2014) includes the following statements:

[…] safety activities are subject to, as far as reasonably practicable, independent layers of provisions, so that in the event that a failure were to occur, it would be detected, compensated or corrected by appropriate measures. The effectiveness of each of the different layers is an essential element of defence-in-depth to prevent accidents and mitigate the consequences should they occur. Defence-in-depth is generally structured in five levels. Should one level fail, the subsequent level comes into play. The objective of the first level of protection is the prevention of abnormal operation and system failures. If the first level fails, abnormal operation is controlled or failures are detected by the second level of protection. Should the second level fail, the third level ensures that safety functions are further performed by activating specific safety systems and other safety features. Should the third level fail, the fourth level limits accident progression through accident management, so as to prevent or mitigate severe accident conditions with external releases of radioactive materials. The last objective (the fifth level of protection) is the mitigation of the radiological consequences of significant external releases through the off-site emergency response.

The design of nuclear power plants (NPPs) is based on a deterministic approach: initiating events (deviations from normal operation, incidents, accidents, hazards) are postulated and used to design all systems, structures and components (SSCs) with design rules that should ensure significant safety margins. Such an approach must be completed by a probabilistic approach that allows considering more exhaustively the combinations of events (initiating events, system and human failures) that could lead to an accident. This is explained below.

The European regulators consider that a continuous improvement of the safety of NPPs is a good practice that should be promoted: this means that NPPs are submitted to periodic safety reviews, possibly associated to safety objectives enhancement. Such periodic safety reviews shall concern all safety issues, including plant ageing, the modifications of the NPP environment (e.g. climatic changes) and any upgrading or modernisation of the plant. The result of such a process should be such that NPPs become progressively safer.

There are a number of organisations at the international level that share experience and good practices, including:

- the IAEA
- the OECD Nuclear Energy Agency (NEA)
- the European Nuclear Safety Regulators Group (ENSREG)
- the Western European Nuclear Regulators Association (WENRA)
- the European Nuclear Installations Safety Standards Initiative (ENISS)
- the World Association of Nuclear Operators (WANO)
- the European Technical Safety Organisation Network (ETSON)
- the Association of the Heads of the European Radiological protection Competent Authorities (HERCA).

The European Commission also promotes a high level of nuclear safety through its tasks in the preparation of Euratom directives. The European Commission JRC coordinates or participates in several nuclear safety scientific research and technical support projects. The Euratom Framework Programs (now Horizon 2020) also provide financial support to European nuclear research and training projects, including risk assessments and nuclear safety projects. For example, the ASAMPSA_E (Advanced Safety Assessment methodologies: extended PSA) project, on risk assessment practices, which is mentioned in this subchapter, and the European Severe Accident Research Network of Excellence (SARNET) have been supported by European Commission funding. Some projects deal with emergency management (EURANOS, NERIS-TP). Through the EU Instrument for Nuclear Safety Cooperation, European and international safety standards are also promoted in third countries.

3.13.3 Lessons from past events

Lessons learned from Three Mile Island (1979), Chernobyl (1986) and Fukushima Dai-ichi (2011) accidents influenced the nuclear industry significantly. They led European Union to set out a common European maximum permitted levels of contamination in foodstuffs following a nuclear accident and develop an early warning system ECURIE, while many EU Member States have installed the networks of radiation measurement stations that have been integrated in an EU-wide monitoring system EURDEP.

3.13.3.1 Three Mile Island, 1979

The Three Mile Island accident occurred on 28 March 1979 in Pennsylvania, USA. Although some risk studies had emerged before 1979 (US NRC, 2016), this accident demonstrated the importance of having an awareness of the potential for core melt accidents among NPP designers and operators. The accident was caused by an incident on the reactor steam generator feedwater system, which led to the automatic reactor tripping. Considering all existing safety systems, this event should not have been the cause of an accident, but some maintenance errors (e.g. wrong valve positions), additional equipment failure (one primary circuit safety valve did not respond to a closure signal from the control room), and a misunderstanding of the reactor status by the operators in the control room led to the melting of the reactor core. This led to significant radioactivity release in the reactor containment vessel. The accident progression was stopped when the operators restarted the injection of water into the reactor vessel.

The offsite radiological consequences were very limited thanks to the design features of the reactor containment vessel. Nevertheless, the accident caused extreme anxiety in the population, despite the fact that the recommendation of evacuation by the nuclear authorities was later cancelled by the governor of Pennsylvania.

Many lessons have been learned from this accident (IRSN, 2013) relating to, for example, the following:

- NPP operator procedures (a combination of symptom-based and event-based procedures is now preferred);
- NPP operator training (accident computer simulation training, accident drills, etc.);
- NPP control room design (reliability of information displayed, alarm processing, etc.);
- additional emergency operating procedures are needed for situations that are not anticipated in the

initial design (loss of the main electrical supply, loss of ultimate heat sink, filtered containment venting procedure, etc.);
- the reactor containment vessel is of prime importance and shall be reinforced where possible;
- precursors of accidents (incidents with no serious consequences) shall be analysed systematically to identify possible weaknesses; this may lead to modifications in NPP design or operation;
- emergency preparedness is of prime importance, with local and national emergency response teams able to support control room operators and to coordinate protective actions for the population;
- research to understand accident progression in the case of a severe accident is needed, and appropriate mitigation strategies shall be developed;
- probabilistic safety assessments (PSAs, see below) shall be developed to identify accidents associated with multiple failures or common cause failures, for which safety improvements may be needed.

3.13.3.2 Chernobyl, 1986

On 26 April 1986 at 01:24, the RBMK (Reaktor Bolshoy Moshchnosti Kanalnyy, i.e. high power channel-type reactor that is a class of graphite-moderated nuclear power reactor designed and built by the Soviet Union) type reactor 4 at the Chernobyl NPP, which had been in service since 1983, exploded in an accident during a technical test. The initial design of the RBMK reactors had some significant weaknesses from a safety standpoint. In particular, they were highly unstable at certain power ranges, the emergency shutdown system had too long a response time and there was no containment around the reactor. In addition, the lack of sufficient preparation for the conditions required for the planned test, and the lack of time in which to complete it, meant that operators did not follow all the operating rules. They also violated these rules by suppressing some important safety systems.

The explosion sent radioactive materials contained in the nuclear reactor core into the atmosphere, to altitudes of more than 1 200 metres. The radioactive plume then propagated in the European atmosphere, then worldwide, and caused the contamination of territories at different level. The areas of Belarus, Ukraine and Russia, which received depositions of caesium-137 exceeding 37 000 becquerels per square metre after the accident, cover a surface area of approximately 150 000 km2 with more than 5 million inhabitants. The accident had huge impacts on the environment (contamination of ground, rivers, forest, agriculture products, etc.), the ecosystem (transfer of contamination through the food chain or agricultural cycles), human health (especially for the 'liquidators' who worked to limit the consequences of the accident and for inhabitants of contaminated areas) and the economy and society in general. Many research programmes have been devoted to the study of the impacts of this accident.

A number of lessons have been learned from this accident (IRSN, 2011), including:

- a new perception and understanding of the consequences of such an accident;
- the importance of emergency preparedness to face such events (national emergency response organisations have been reinforced in most countries);
- the importance of transparency and providing information to the public: an EWS, ECURIE (European Community Urgent Radiological Information Exchange), has been elaborated that allows each country to immediately inform all EU Member States in the event of an accident in one of its nuclear facilities; a dedicated European Directive (EU, 1989) defines common requirements on informing the general public in the event of a radiological emergency and some countries have significantly reinforced the legal basis for such transparency (e.g. France; see French Nuclear Safety Authority, 2006); an International Nuclear Event Scale has been defined to ensure clear understanding of the severity of various events;
- the need for common European maximum permitted levels of contamination in foodstuffs following a nuclear accident, which have been set out in a related Council Regulation issued in 1987 (Euratom, 1987);
- for the overall radiological surveillance of the environment, EU Member States have installed radiation measurement stations; these national networks have been integrated in an EU-wide monitoring system EURDEP (European Radiological Data Exchange Platform; a standard data-format and network for exchanging radiological monitoring) which is managed by the European Commission;
- in terms of plant design and operation, the accident has promoted the

safety culture (under an interrogative and prudent approach, the test at the origin of the accident would not have been carried out) and the importance of the appropriate application of the defence-in-depth concept (despite human error, other lines of defence should have prevented such a disaster).

For new reactors, European regulators consider that such accidents with large radioactive release shall be 'practically eliminated' and they require an appropriate demonstration of the various safety features (RHWG, 2013). This requirement has a considerable impact on reactor design features.

3.13.3.3 Fukushima Dai-ichi, 2011

The Fukushima Dai-ichi accident was initiated by the Great East Japan earthquake that occurred on 11 March 2011 with a magnitude of 9. It caused a tsunami that struck the Japanese coasts, with waves exceeding 10 metres. The devastation in Japan was considerable: more than 15 000 people were killed, 6 000 were injured and 2 500 reported missing, and the destruction of buildings and infrastructure was considerable.

Lessons learned from Three Mile Island (1979), Chernobyl (1986) and Fukushima Dai-ichi (2011) accidents influenced the nuclear industry significantly.

The earthquake did not threaten the Fukushima Dai-ichi NPP's safety functions, but the resulting tsunami submerged the NPP's platform and led to the loss of the ultimate heat sink and most internal electrical supplies. Four out of six reactors stayed in long-term station black-out conditions. The site staff, despite their best efforts and considerable courage, could not prevent core melt at units 1, 2, and 3 and the resulting hydrogen explosions and large radioactive release in the environment. This caused a nuclear catastrophe in addition to the earthquake and tsunami impacts. Although the winds were mostly directed towards the sea during the accident, the ground contamination by the radioactive plume led to the evacuation of 80 000 inhabitants (a number that rose after a 'voluntary' evacuation starting on 25 March) and had huge impacts for agriculture, ecosystems, the economy and society in general in the region of Fukushima. The contamination of the ocean by liquid releases also had impacts on the fishing industry. The IAEA report (2015) provides a description of the accident, its consequences and all remediation efforts.

The accident led European countries and many others to develop a stress test programme to assess the capacity of NPPs to withstand extreme conditions (ENSREG, 2012). The robustness of NPPs has been assessed in terms of three major topics:

- protection against extreme external hazards (earthquake, flooding, etc.);
- NPP controls in the event of a loss of ultimate heat sink or electrical supply;
- severe accident management protocols.

Most NPP operators have decided to implement additional provisions on their utilities to further increase their robustness and the protection of population. The European regulators and the IAEA have also promoted the concept of 'design extension conditions' (IAEA, 2016; WENRA, 2014). The idea is to extend the basic design of NPPs to account for more adverse conditions for which a reactor can still be maintained in a safe state, or for which a severe accident (with core damage or spent fuel damage) can be controlled to recover a stable state without any significant radioactive release into the environment.

After the Fukushima Dai-ichi accident, most countries decided that NPP reinforcements must be able to face extreme conditions. Such reinforcements should enable the following:

- site protection against hazards (extreme flooding, winds, etc.);
- implementation of additional protected (bunkered) safety systems or the reinforcement of some existing structures, systems and components;
- implementation of additional fixed or mobile equipment to allow plant stabilisation in extreme situations;
- implementation of new infrastructure and equipment for emergency response management (reinforced emergency building, reinforced mobile equipment storage, additional communication and transport means, improved protection against radioactivity);
- more staff responsible for emergency actions;
- improvement of severe accident management strategies and, for some NPPs, the implementation of new equipment.

In relation to emergency preparedness and response, existing and reinforced requirements have been integrated into the revision of the European Basic Safety Standards directive (EU, 2013); the directive gives an increased focus on the need for international cooperation. The emergency management plans have been improved or are in revision in many countries (see HERCA-WENRA scheme for severe accidents, change in pre-planning radii for evacuation, sheltering and iodine distribution). Research in this area was promoted via the PREPARE and the recently started CONCERT project.

This has led to post-Fukushima action plans on a national level as well as to enhancements of the safety standards at international (IAEA, WENRA, etc.) or national levels.

Although NPP modifications have been decided, the Fukushima Dai-ichi accident has led to an increased interest in the study of natural and man-made hazards that could threaten a nuclear site and in the development of an on-site and off-site emergency response organisation that is capable of facing any complex situation.

3.13.3.4 High-amplitude external hazards at nuclear power plant sites

Nuclear power plants should be designed to withstand any high-amplitude external hazards that could threaten safety functions. Nevertheless, a number of high-amplitude events have caused problems at some nuclear sites. This is an important challenge for the safe operation of NPPs, and many countries, such as France, include a re-assessment of external hazards at each 10-year periodic safety review. If the safety margins appear to be reduced in light of the most recent knowledge (e.g. on earthquake, flooding risks or more general climatic changes), then NPP reinforcements can be decided. To illustrate this topic, a survey has been carried out by the ASAMPSA_E project (ASAMPSA_E, 2013) on more than 80 high-amplitude external hazards that have been experienced by NPPs or other facilities and high-amplitude external hazards described in the IAEA Incident Reporting System (IRS) database. Table 3.7 provides some external hazards that could be experienced by nuclear facilities identified by ASAMPSA_E.

Meteorological events are the most frequent, followed by biological infestation events. 'Low air temperature' seems to be the most recurrent hazard, followed closely by 'Lightning' hazards. Infestation with marine organisms has been observed more often than infestation with vegetable materials (such infestation may threat the ultimate heat sink of NPPs).
The Fukushima Dai-ichi accident showed the importance of the combinations of hazards. This fact was also identified in France during an event at Le Blayais NPP in 1999 (a combination of a storm, high tide and waves led to the partial submersion of the NPP platform). This event led to the significant reinforcement of certain French NPPs against flooding, but perhaps not to an international awareness of the importance of combinations of hazards in risk assessments.

All the above show the importance of enhanced investigations of all credible external hazards, including all their possible correlations and combinations. This has led to the analysis of the impact of 'rare events', which is a challenging activity for the engineering sector.

3.13.4 Safety assessment methodologies

The design of NPPs follows a set of rules and practices that should ensure a high level of safety. Standards have been developed, then improved, in a number of areas, from high-level considerations (IAEA, 2016; WENRA, 2014; RHWG, 2013) to more technical ones (e.g. rules for mechanical design).

An important step in demonstrating the safety of a NPP design is to identify a set of accident conditions that are applied to design all safety-related SSCs of the NPP. These accident conditions result from initiating events (equipment failure, human errors, internal or external hazards) leading to NPP transients, which are then analysed using specific conservative assumptions to ensure safety margins. The examination of this set of accident conditions using conservative assumptions is the so-called deterministic safety assessment. The methods that are applied must be sufficiently simple for the feasibility of the design and its safety demonstration, and sufficiently robust to ensure that the NPP and its organisation can be resilient to any event during plant operation.

To improve the safety demonstration, and as a complementary approach to the deterministic approach, probabilistic safety assessments (PSAs) are developed. A definition of the three levels of PSA can be found in IAEA Safety Standards SSG-3 (IAEA, 2010a) and SSG-4 (IAEA, 2010b):

'PSA provides a methodological approach to identifying accident sequences that can follow from a broad range of initiating events and it includes a systematic and realistic determination of accident frequencies and consequences. In international practice, three levels of PSA are generally recognised:

1. *In Level 1 PSA, the design and operation of the plant are analysed in order to identify the sequences of events that can lead to core damage and the core damage frequency is estimated. Level 1 PSA provides insights into the strengths and weaknesses of the safety related systems and procedures in place or envisaged as preventing core damage.*

2. *In Level 2 PSA, the chronological progression of core damage sequences identified in Level 1 PSA are evaluated, including a quantitative assessment of phenomena arising from severe damage to reactor fuel. Level 2 PSA identifies*

TABLE 3.7

External hazards that could be experienced by nuclear facilities

Earthquakes Tsunamis Ground subsidence	Flooding High tides Storm surges Wind waves High river levels/flow Spring runoff (from mountains)	High winds Hurricanes Tornados Projectiles driven by high winds Salt storms	Blackout Electrical disturbance transmitted by the external power grid Malware computer programs or computer viruses Electromagnetic interference Disturbance by high-frequency radio signals Oil spills Transport accidents Aircraft crashes External fire due to human activity External explosion Corrosive liquids or gases Toxic liquids or gases Radioactive releases Pandemics/severe epidemics
Biofouling Jellyfish infestation Small fish infestation Mollusc infestation Shell infestation Vegetable material in the heat sink Reeds intrusion Algae Rat infestation	Low water temperature Frazil Ice in cooling water Frost	Lightning Solar flares, solar storms, geomagnetic storms	
Sand deposits Silting Small rocks Sediments	Low air temperature High air temperature Low river levels	Extreme rain Heavy snowfalls Wet snow Atmosphere moisture Hail Freezing rain	Forest fire

ways in which associated releases of radioactive material from fuel can result in releases to the environment. It also estimates the frequency, magnitude, and other relevant characteristics of the release of radioactive material to the environment. This analysis provides additional insights into the relative importance of accident prevention, mitigation measures, and the physical barriers to the release of radioactive material to the environment (e.g. a containment building).

3. *In Level 3 PSA, public health and other societal consequences are estimated, such as the contamination of land or food from the accident sequences that lead to a release of radioactive material to the environment.*

PSAs are also classified according to the range of initiating events (internal and/or external to the plant) and plant operating modes that are to be considered.'

The PSA methodology is based on event tree methodologies, which are conceptually simple but highly complex in detailed applications. This is due to the number of SSCs in a NPP, the variety of initiating events, the possible equipment and human failures, the interdependencies between events, the uncertainties in data (hazards modelling, equipment failure probability, human failure probability, physical phenomena progression, SSCs behaviour in unplanned circumstances, etc.). A PSA modelling exists for almost all NPPs. Their quality is progressively improving, thanks to periodic updates and experience sharing. For example, the OECD-NEA working group risk (WG-Risk) collects and shares international experience in this area.

Although this approach is quite advanced for NPPs, PSA experts recognise in general that these studies still have some weaknesses and continual improvements are performed. One weakness is often the completeness of initiating events and hazards considered, which varies from one PSA to another.

Standards have been developed to design NPPs that should ensure a high level of safety. An important step in demonstrating the safety of a NPP design is to identify a set of accident conditions. To improve the safety demonstration probabilistic safety assessments are developed.

The ASAMPSA_E project was initiated in 2013 to help increase the scope of existing PSAs. For this project:

'An extended PSA (probabilistic safety assessment) applies to a site of one or several Nuclear Power Plant(s) (NPP(s)) and its environment. It intends to calculate the risk induced by the main sources of radioactivity (reactor core and spent fuel storages, other sources) on the site, taking into account all operating states for each main source and all possible relevant accident initiating events (both internal and external) affecting one NPP or the whole site.'

Some general lessons can be identified (Raimond, 2016):

- an extended PSA is still an objective for most PSA teams working on NPPs: no NPP site currently has a PSA that covers:
  - -full-power and all reactor shut down-state initial states
  - -all sources of radioactivity
  - -all relevant types of initiating events (internal and external)
  - -multi-unit accident management
- there is a need to enlarge the analysis scope in terms of the NPP, the neighbouring reactors or other industries, the environment at a medium scale;
- the risk metrics to be used are still a topic for discussion, especially if the objective is to calculate some 'global risk';
- PSA experts have to decide, for each NPP, which initiating events should be included in the PSA. Criteria are applied to identify risk significant events but, for some initiating events (e.g. high-amplitude earthquakes or combined extreme weather conditions), high uncertainties exist in both their frequency and amplitude; in such cases, the PSA approach is questionable;
- the geosciences fail sometimes to calculate both frequencies and features of some rare (extreme) natural events for PSA with reasonable uncertainty bounds; this is, in fact, a societal concern and progress in these areas should be expected;
- the study of the impact beyond design hazards may require additional methodologies (e.g. impact of beyond design lightning strike);
- PSAs have been applied to single NPPs; PSAs for multiple NPP sites have rarely been undertaken; the feasibility and interest of such

studies are ongoing issues;
- the application of PSAs (or extended PSAs) in decision-making processes is still a topic for harmonisation: for example, the recent interest in rare extreme events functions as a reminder of the need to take into account uncertainties in decision-making processes.

3.13.5 Risk reduction, a multiform activity

As explained above, European nuclear stakeholders apply the concept of continual safety improvement. This is done with a risk-reduction perspective. PSA has a role in this process, but many other considerations are taken into account. Risk reduction is in fact a multiform activity that cannot be reduced to a simple list. Some examples are proposed below but they cover only a limited number of risk-reduction possibilities, which are in fact possible at each level of the defence-in-depth approach.

For new reactors, the protection of the population in the event of a severe accident is paramount, as indicated by WENRA (2014):

' reducing potential radioactive releases to the environment from accidents with core melt, in short and long term, by following the qualitative criteria below:
- *accidents with core melt that would lead to early or large releases of radioactive material should be practically eliminated;*
- *in the event that accidents with core melt do occur, design provisions should have been be made so that only limited protective measures in area and time are needed for the public (e.g. no permanent relocation, no need for emergency evacuation outside the immediate vicinity of the plant, limited sheltering, no long term restrictions in food consumption) and sufficient time must be available to implement these measures.'*

Several safety authorities request that utilities upgrade existing reactors to meet, as far as possible, the objectives for new reactors. In particular, it shall be postulated that severe accident may happen and that, in such cases, accident mitigation strategies shall be implemented. This obviously contributes to some degree of risk reduction, at least if the other existing safety features are not degraded as a result of ageing.

Risk reduction is a multiform activity that cannot be reduced to a simple list. There are a number of risk-reduction possibilities, which are in fact possible at each level of the defence-in-depth approach.

Research activities are very important to ensure the continued interrogation of existing practices, to develop new knowledge and to promote the application of new knowledge in safety improvements. Some examples are described here but, in fact, there are numerous topics of interest (e.g. see NUGENIA, 2013):

- the reassessment of hazards is an important issue during periodic safety review; as explained above, for natural hazards, there are topics where geosciences provide highly uncertain information due to remaining uncertainties for rare events but, nevertheless, even if the quantification of hazard features is difficult, reinforcement of NPPs can be decided based on the most recent knowledge;
- the analysis of NPPs' responses in the event of an accident using simulation tools capable of providing best-estimate information for the design verification of SSCs or the development of operating procedures;
- the analysis of SSCs' response (fragility analysis) in the event of hazards (earthquake, flooding, fire, lightning, etc.);
- techniques for in-service inspection to check the capability and conformity to safety standards of all key safety equipment (e.g. pipe welding control, risk informed inspection, plant walkdowns);
- research on severe accident progression;
- research on accident precursors;
- research on human factors and organisations: how to evaluate the efficiency of organisations to ensure the efficiency of all human activities (during NPP design, construction, normal operation, modernisation, control, accident management, etc.).

The emergency response is also a crucial factor during accident management. This concerns the site in question (to help manage a complex situation at a local and national level, to ensure the dissemination of transparent information), the public authorities (to decide protective actions for the populations, to disseminate information transparently to the public) and international exchanges (the consequences of a nuclear accident are transnational; rescue solutions can often be found at the international level, and immediate and transparent communication is expected from any country facing a nuclear accident). As mentioned above, many research activities support progress in emergency response capabilities, for example on source term prediction, simulations of radioactivity transfer in environment, rules for the protection of populations, rules for agriculture management and communication during and after the accident (see EURANOS, NERIS-TP and PREPARE projects).

In addition, it is also recognised that the organisation of the control of nuclear activities by official bodies (in general nuclear safety authorities and technical safety organisations) and the relationship between the industry and these official bodies are of primary importance in risk reduction. Relationships with NGOs also have to be considered carefully.

We can mention, as an example, some values generally shared by the safety authorities or the Technical Safety Organisations, namely competence, independence, rigor, transparency impartiality, proactivity or initiative. The efficiency of the control of nuclear activities is another topic for exchanges at the international level.

3.13.6 Conclusions and key messages

Partnership

To conclude, we wish to highlight the importance of the multiform activities conducted to prevent any accident or to limit its consequences should one occur. The fundamental safety principles and the defence-in-depth approach underlie these multiform activities, which intend to enhance the nuclear safety requirements, the design features of nuclear facilities, the quality of construction, all human activities during normal operation and, in response to accidental situations, the continuous safety improvement and the control by appropriate bodies.

Knowledge

The efficiency of the emergency response plans at local, national or international levels and of the related international cooperation remains a challenge for the nuclear industry, and good practices can be shared with other activities. In parallel, research on the resilience of human organisations when facing complex situations can be promoted in the nuclear industry and in many other areas.

Innovation

The nuclear industry has still to face many challenges to maintain and improve the safety of operating and new reactors. Among these challenges are the human and organisational factors (training and education, generation renewal, changes in competences, evolution of requirements and regulation, modernisation programmes, the organisation's efficiency, etc.), the ageing of the nuclear facilities and the financial context.

If some challenges are very specific to nuclear activities, others are fully cross-connected to other human activities. For example, the study of high-amplitude natural hazards has become increasingly important since the Fukushima Dai-ichi accident, and efforts are being made to reinforce nuclear facilities if needed. Understanding and predicting these natural hazards is a societal concern and progress in geosciences is expected. To support safety studies for nuclear facilities, seismic faults identification and modelling, the quantification of correlated natural hazards (typically during extreme weather conditions) or the regional analysis of the consequences of such natural hazards are topics of interest for which knowledge should be improved.

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3.12 Technological risk: chemical releases

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