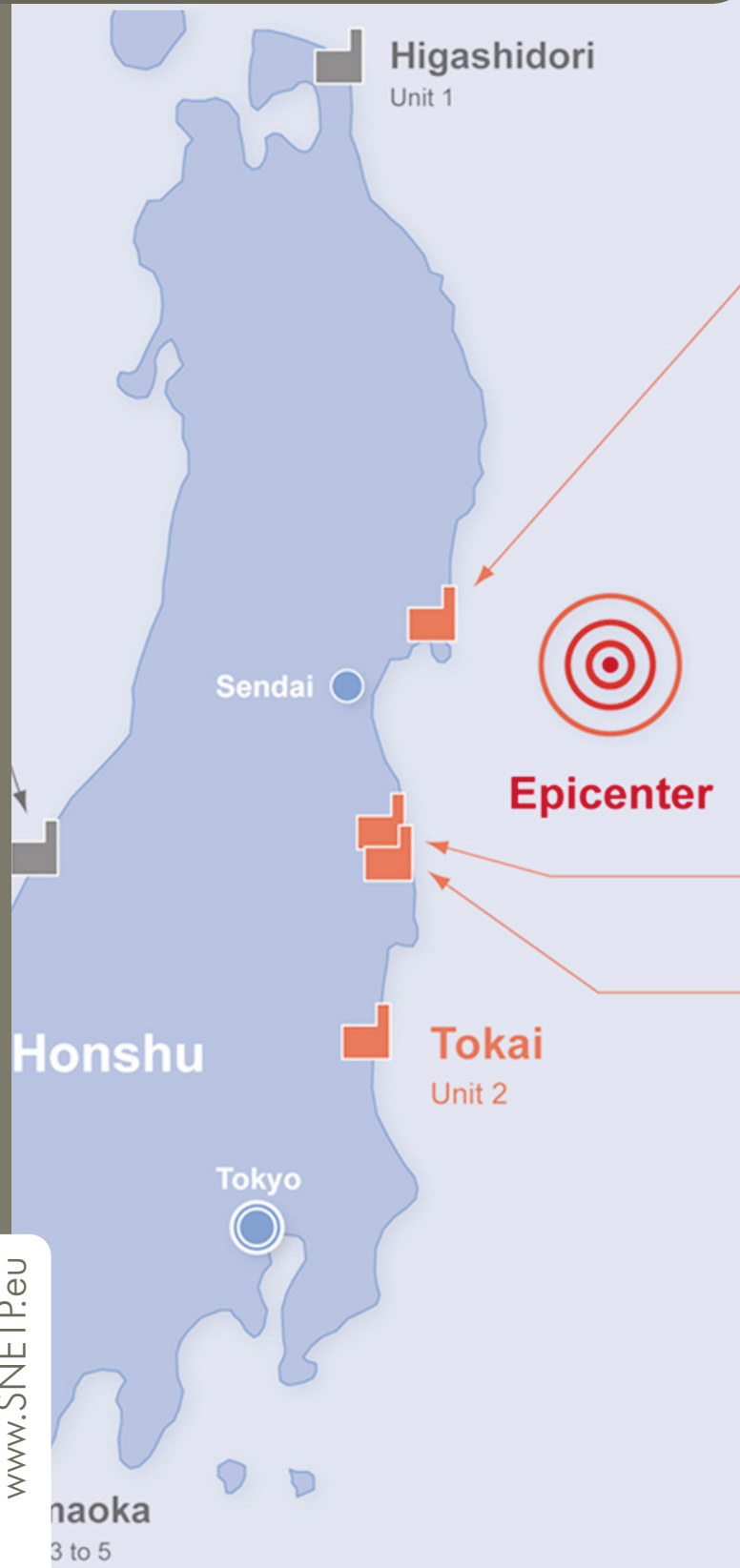


Identification of Research Areas in Response to the Fukushima Accident

January 2013

Report
of the SNETP
Fukushima
Task Group





This document has been prepared by the Fukushima Task Group established within the Sustainable Nuclear Energy Technology Platform.

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Foreword by the chairman

In response to the Fukushima accident, on March 31st, 2011, the Governing Board of the Sustainable Nuclear Energy Technology Platform decided to establish a Task Group with the main objective to assess implications of the accident on the medium and long term research and development Platform's programme. It was clear that the most meaningful response to Fukushima is to learn and convert the lessons learned into better knowledge and subsequent safety improvements of current and future reactor systems, and that the research and development should be one of the main contributors to achieving this goal.

Large and fast growing volume of relevant information has been collected and evaluated as a basis for the Group's work. The report focuses on research associated with safety of nuclear power plants with emphasis on robustness of the plants against extreme hazards, on prevention and mitigation of severe accidents including organizational and societal factors, and on

mitigation of accident consequences. The Group concluded that although the Fukushima accident does not require completely new research directions, it is appropriate specifying or updating priorities in certain areas. Findings of the Group, with identification of specific research priorities for 13 thematic areas, are summarized in this report. Many suggestions formulated for existing plants are also applicable to new reactor designs.

The ideas included in the report have been presented by members of the Group in several technical meetings, and already reflected in the updated SNETP Strategic Research and Innovation Agenda. The Group is confident that the report will help the nuclear community in better determining future research directions. It should be however understood that information about the Fukushima accident is still uncertain and not complete. The report should be therefore considered as live document which may be subject to future updating.

Jozef Misak,
Chairman of the Fukushima Task Group

Executive summary

■ 1. Introduction

The accident which occurred at the Fukushima Dai-ichi nuclear power plant (NPP) on March 11, 2011, raised public concern on nuclear energy and drew a new attention to the safety of NPPs, in particular in case of extremely severe external hazards.

A number of initiatives have been undertaken in many countries and at international level in order to take into account the lessons learned from this accident for the improvement of nuclear reactors design and the organization to manage radiological accidents. It can be quoted the OECD/NEA ministerial seminar on June 7, 2011 the safety authorities' forum on June 8, 2011 and the ministerial conference organized by the IAEA from 20 to 24 June, 2011 which resulted in the Action Plan on Nuclear Safety approved by the Board of Governor and endorsed by the IAEA general conference.

Most of the countries operating nuclear reactors have launched systematic reassessment of the safety margins of their nuclear fleet under severe natural hazards, usually called stress-tests. A comprehensive stress tests process has been launched by the European Council under the European Commission coordination.

Most Nuclear countries have launched systematic reassessment of the safety margins

SNETP gives nuclear safety the highest priority in its vision and Strategic Research and Innovation Agenda (2013-SRIA). European technical safety organizations (TSOs) are involved in the activities of the platform governance and working groups. SNETP

promotes safety related research and harmonization at European level, for current and future generation of nuclear fission technologies. This is the reason why the SNETP Governing Board decided to empower a Task Group to investigate how the first lessons learned from Fukushima accident could impact safety related R&D orientations and priorities.

In its investigations, the Task Group concentrated on medium and long term R&D, in particular on the developments, updating and validation of methods and tools for areas which are not considered as adequately covered up to now. Of course, it is understood that a broad ranging multidisciplinary and synergic approach to reflect fully the lessons learned from Fukushima should be foreseen. An example of an additional factor contributing to further improvements in the safety margins is testing of systems and components aimed at a better quantification of safety margins. Even if the topic has been only marginally addressed in the Task Group's work, identification of appropriate existing – and future – experimental facilities and relevant tests should be also considered.

This report addresses high level orientations that will be further detailed by SNETP Technology Task Groups (NUGENIA, ESNII and NC2I). On longer term – in several years – the outcomes of the future expertise acquired on the four reactors and fuel pools of Fukushima Dai-ichi site will be very valuable for the qualification and validation of the results of the proposed R&D tasks.

This report should be thus considered as a first step of the process, but it already catches important features which are summarized below.

■ 2. What are the main challenges revealed by the Fukushima accident?

The Fukushima accident was triggered by the combination of two initiating events:

- An exceptional magnitude earthquake which caused the sudden total loss of almost all the off-site power supply. The reactors 1-2-3 which were in operation have been automatically shut-down. The residual heat removal systems were started immediately after, relying on electricity supplied by emergency power sources (diesel generators and batteries).
- The associated tsunami caused the flooding of the site by a wave about twice the size considered previously in the safety evaluation. It led to both the loss of all the emergency power supply systems and of the heat sink.

The immediate challenge for the emergency response team was to recover cooling capabilities in a situation where the off-site power supply has required about 11 days to be effective. This situation has affected all 4 reactors and the spent fuel pools. A detailed analysis of the system deficiencies which caused the loss of emergency cooling systems is still difficult to perform due to the lack of information but nevertheless, according to the current knowledge of the accident, the efficiency and the reliability of the decision making process during this extreme event were not optimal.

The challenges identified from the lessons learned are the following:

- To enhance further defence-in-depth capabilities for any type of initiating events, especially for severe natural hazards and any their combinations. It should be considered for existing reactors, future Gen III reactors as well as for the development of Gen IV reactors.
- To address more systematically at the design stage the plant features for coping the design extension conditions (beyond design basis accidents) to assure the robustness of the defence in-depth and to avoid cliff edge effects. The approach should include situations where several units on the same site are affected by a beyond design basis event.
- To develop multiple and more robust lines of defence with respect to design basis events and design extension conditions to define additional measures to be considered in the design.

A special emphasis has to be put on the emergency management which has been challenged during the accident due to:

- The concomitance of many events, the severe environmental conditions and the mutual interaction between the affected units on site.
- The complexity and the difficulty of the decision making process which has altered the effectiveness and the promptness of the actions and which has generated both confusions and delays.
- The difficulties to recover a suitable and stable electrical supply source during several days.

Improvements of the emergency preparedness and response should consider:

- The availability of more sophisticated tools to provide the operators with more reliable and quick monitoring of the plant status and prediction of the accident progression to help in the implementation of an appropriate recovery strategy.
- The availability of redundant intervention means in the vicinity of the site.
- An enhanced coordinated international cooperation/expertise which could provide help in the plant status diagnosis, in the prognosis for the situation evolution and on the mitigation strategy.

■ 3. Identification of relevant research areas

Safety related R&D tasks are already included in the main orientations of the SNETP 2009 SRA and, in particular for the current reactors, specific actions are proposed related to the long term operation and to severe accident management. The R&D effort is largely shared through EURATOM framework programme and, at broader international level, through the OECD/NEA programmes. The R&D on severe accidents has in particular the objective to produce knowledge, methods and codes to assess risks for beyond design situations.

Ongoing investigation of the Fukushima accident is influencing the scale research priorities with a more specific focus on extreme external events and their combinations, on common mode failures and human behaviour, with subsequent assessment of the impact the robustness of the defence in depth.



The Task Group has identified 13 main areas of research, focused on siting, design and operation of NPPs. These areas are briefly described below.

a. Systematic assessment of vulnerabilities to defence-in-depth and safety margins for beyond design basis loads

The main objective of this area is to develop a systematic methodology for the determination of evaluation safety margins and the evaluation risk of occurrence of cliff-edge effects for extreme events beyond the design basis.

The methodology should include the identification of rare extreme events potentially leading to common cause failures of multiple plants system, analysis of their consequences and the effects of interrelation between plant systems and operators actions. The R&D tasks should also include the development of complex models for the behaviour of NPPs under extreme loads beyond the design basis and the determination of the ultimate capacity of physical barriers and of the integrity of the reactor containment.

Further improvement in the safety margins could be achieved through extensive testing and/or re-testing systems and components against e.g. seismic loads. Identification of current and future experimental facilities able to host such test would valuably contribute to safety.

b. Human and organizational factors under high stress and harmful conditions

Fukushima accident revealed the importance of human and organizational factors under high stress and harsh working conditions, affecting the decision-making process. The human response to these challenging conditions should be explored in more detail, in order to identify feasible and efficient ways to improve the emergency preparedness and the response to a severe nuclear accident, including development of supporting tools and procedures.

c. Improved methods for external event hazard evaluation

The focus of this area is to enhance and harmonize the methodologies for the

assessment of external hazards and for their combination as well as their effects on NPPs. The methodologies should be updated on the basis of the state of art knowledge in earth science and may also consider man-made hazards (airplane crash, missile impacts, cyber-attacks, malevolent acts).

d. Use of the probabilistic methods to assess plant safety in relation to extreme events

To complement the deterministic approach, PSA is performed with a systematic approach making use of realistic assessments of the performance of equipments and operators. PSA has the potential to provide a deep understanding of the potential risk resulting from the operation of a NPP over wide range of conditions.

The main objective is to extend the present PSA methodologies to extreme events with very low frequency. It should take into consideration such factors as the availability of site infrastructure, the prolonged station black-out and the potential loss of ultimate heat sink, which are “traditionally” out of the scope of PSA. This type of analysis should also consider human reliability and behaviour under such circumstances.

e. Advanced deterministic methods to assess plant safety in relation to extreme events

The works in this area should focus on improvement and harmonisation of the traditional deterministic methods for the assessment of the damage to structures, components and systems of NPP under various extreme loads beyond the design basis. Updated methods should address extreme loads and their combinations, and determine the measures for the elimination or mitigation of the damage.

f. Advanced safety systems

The Fukushima accident and in particular the long term duration of the loss of electricity supply highlighted the potential interest in passive systems or, more generally, in safety related equipment and components based on

passive rules. The main objective of future investigation should be to demonstrate the actual capability of such systems to guarantee the residual heat removal under extreme accident scenarios (prolonged station black-out, loss of infrastructures, loss of instrumentation, and reduced accessibility to the plant).

Research in this area should also address the development and the qualification of numerical tools for the 3D simulation of relevant phenomena like multiphase natural circulation and heat exchange where challenges still exist for getting reliable results.

g. Advanced materials for nuclear power

SNETP supports ongoing comprehensive R&D programmes on advanced materials for nuclear power which are performed under the umbrella of the European Energy Research Association (EERA). The main objective is to develop, test and model the behaviour of existing and new structural material for nuclear components, taking into account the harsh conditions (corrosive environment, high radiation dose exposure, and high frequency thermal and mechanical fatigue).

h. Advanced methods for the analysis of severe accidents

The main objective is to review the state of the art and to enhance and validate robust models and simulation platforms for the analysis of severe accidents.

Works in this area should continue in on-going research programmes with focus on phenomena which are not yet adequately understood, such as post accidental heat removal, coolability of overheated and partially relocated reactor core, in-vessel core melt progression, in-vessel molten corium retention, corium stabilization in containment, molten-core-concrete-interaction and hydrogen generation and behaviour in the containment.

i. Improved procedures for management of severe accidents

The main objective is to enhance the overall level of knowledge, skills, predictive tools and

strategies applicable for severe accident management (including conditions of long term loss of electricity supply, loss of heat sink). The tasks include investigations on reliable monitoring and communication tools under harsh severe conditions.

j. Assessment of the radiological effects of the severe accidents

This area should provide for support to of existing R&D programmes in order to update and validate models for determination of the source term, for dissemination of radioactive substances and for assessment of the radiological impact of the releases on the human health and on the environment. It may include harmonization of the intervention levels for radiological accidents and reconsideration of the INES scale as a tool for communication with the public.

k. Improved modelling of fuel degradation in spent fuel pool

The main objective of this area is to improve the knowledge of the fuel degradation phenomena and failure modes for fuel assemblies stored in the spent fuel pools and to develop and validate the modelling tools.

The R&D actions should consider the scenarios with the dry out of the pool and the following reflooding phase including the effect of the possible presence of debris that may fall down into the pool.

l. Methods for minimization of contamination in the NPP surroundings and for treatment of large volume of radioactive waste

Assessment of the radiological conditions in a wide area around the NPP and mitigation of the effects of contamination on the population and the environment have been key challenges since the beginning of the Fukushima accident to the present day, and will remain relevant for the next years.

The ultimate goal in this area covers the complete renovation and restoration of contaminated territory. Effectiveness of existing methods for radiological environmental



monitoring as well as availability of suitable technical means for the rehabilitation of potentially contaminated territory should be evaluated and attention should be paid to the methods for the isolation and fixation of the radioactive materials released outside the NPP.

m. Accident management in the framework of the integrated rescue system

Problems encountered in the management of Fukushima event claim for updated methods for the evaluation of the radiological status on the site and in the surrounding, for supporting important decisions like evacuation and for the improvement of the integrated rescue systems at the national and international level. Also, the way to communicate the radiological data to the public needs to be improved for a more clear understanding of the actual level of the threat.

■ 4. Conclusions

Despite Fukushima's accident, the nuclear energy remains an important component for the European energy mix and also represents a significant contribution to cover the worldwide energy

needs. It is the responsibility of the nuclear energy stakeholders including SNETP to benefit from the lessons learned from the Fukushima accident.

Research and development are essential tools for a better understanding of the phenomena and, thus, are necessary to derive practical indications to enhance the prevention and the mitigation of severe accidents.

No really new phenomena were revealed from the Fukushima accident and the basic orientations of the SRA are still valid. However the specific research areas identified in this document shall be considered with the appropriate priority given to them in the update of the SRA. In particular, the issues related to rare extreme events severe accidents should be considered in a more comprehensive approach to safety in order to better quantify the design margins and understand the behaviour of NPPs under beyond design basis scenarios. The R&D activities identified in the current document should continue playing an essential role in future utilization of nuclear power, supporting the life extension of the current LWRs, which should be associated with comprehensive safety assessment using up to date standards, the deployment of the Generation III reactors and the development of the Generation IV technologies, always keeping high safety level as utmost priority.

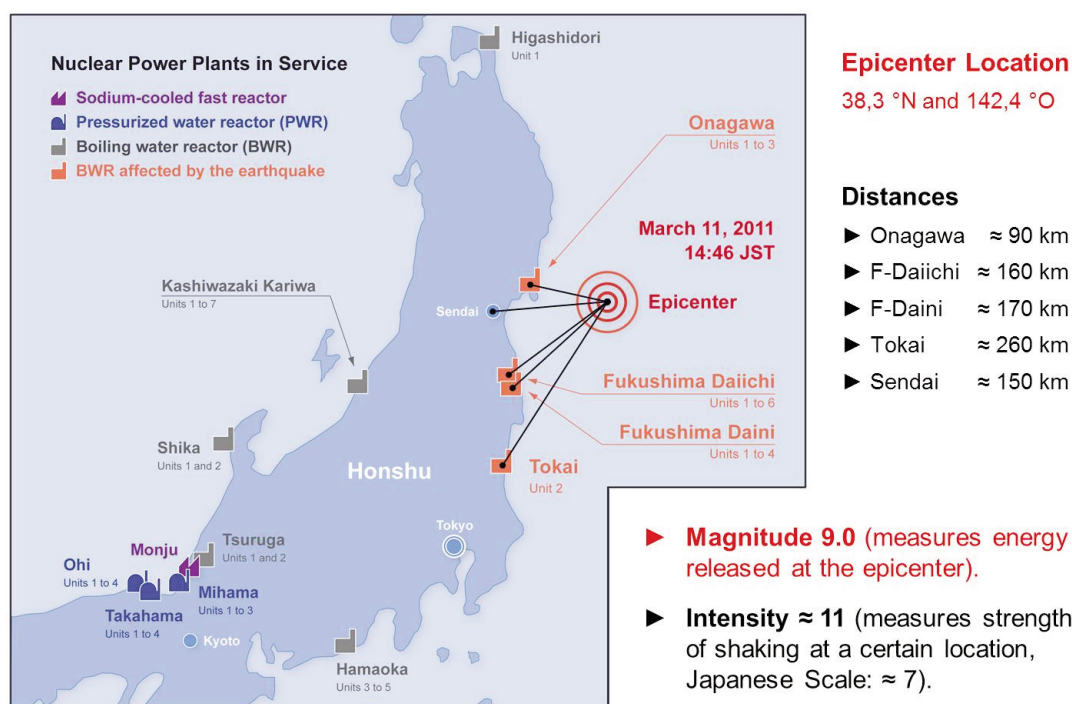


Figure 1 - Nuclear power plants in service in Japan (source " VGB, GRS)

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1. Introduction

The accident which occurred on 11 March 2011 led to the destruction of four nuclear reactors at the Fukushima Dai-ichi nuclear site and again drew attention to the safety of NPPs. Although the causes, course and consequences of the accident were strongly linked to the given location and to a specific type of a boiling water reactor, utilizing lessons learned about the possibility of a severe accident with radiological consequences, due to failures with a common cause, is also relevant for other sites and for other types of reactors.

Following the accident, a number of initiatives have been undertaken by all stakeholders of the nuclear-energy sector, including designers, manufacturers, operators and supervisory bodies of nuclear facilities in many countries. These initiatives were established in order to learn from the accident and to utilize the lessons learned for further safety improvements. In accordance with the principles of feedback of operating experience, operators of nuclear facilities have done and continue to perform assessment of the safety margins and adopt measures to increase the safety level of the plants named stress tests. National regulatory bodies, international organizations and European Commission (EC) were also extensively involved in reviewing the stress test reports.

It is clear that after these immediate steps, the lessons learned from Fukushima in the medium and long term will be reflected also in the design requirements for NPPs, in international safety standards, regulations issued by national supervisory authorities, operational procedures, emergency planning, etc. All of these forthcoming steps should be based on the updated level of knowledge, which should be the product of comprehensive research and development projects.

Nuclear safety related research and development (R&D) constitutes an important base for safety improvements and accident prevention. The

Sustainable Nuclear Energy Technology Platform (SNETP), as the European platform with the overall goal to enhance the sustainability of nuclear power by supporting technological development, should definitely reflect implications of Fukushima into its own activities, in particular in nuclear safety related research. With this objective, the SNETP Governing Board at its 7th meeting held in Rome, 31 March 2011 decided to establish a Task Group in order to:

- Assess the lessons learned from the accident.
- Assess the results of the stress tests.
- Assess the implications for SNETP on Generation II/III (Gen II/III), as well as on other components of the Platform.
- Make proposals to SNETP (and possibly in turn, to the SNETP Board or to the EC).

The focus on R&D distinguishes the Task Group from the other groups and initiatives that already have issued reports on lessons learned from the Fukushima accident.

Coherently with its mission, and in consideration of the work already done by the various organisations, the Task Group has concentrated its attention on medium and long term R&D tasks, in particular on development, updating and validation of methods and computational tools for those areas which are not considered as sufficiently well understood. Of course, it is acknowledged that a broad ranging multidisciplinary and synergic approach to reflect fully the lessons learned from Fukushima should be foreseen.

The results of the Task Group's work are summarized in the current document. Reflecting the Fukushima accident, it is more focused on light water reactor technology. Nevertheless, the authors believe that many of the general implications and areas for additional research and development are applicable for other

nuclear installations and reactor designs, including Gen IV reactors.

This document is intended to be a “high level” one, assuming that more detailed tasks will be elaborated by the three technological WGs of the SNETP, i.e. NUGENIA, ESNII and NC2I.

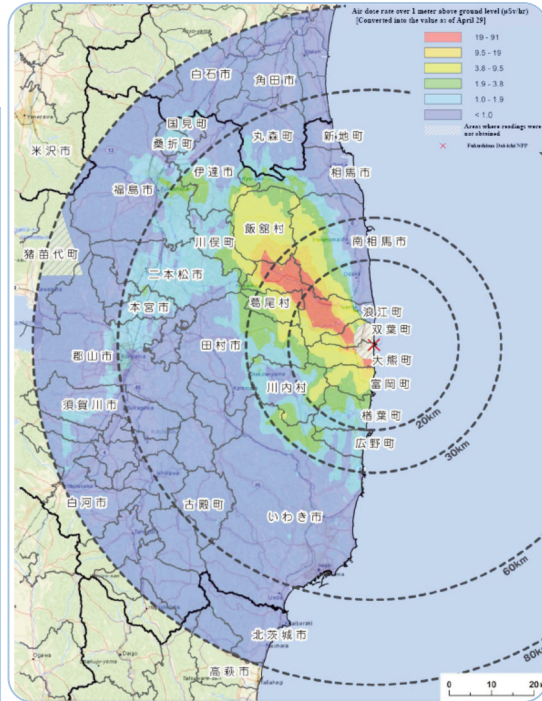


Figure 2 - Air dose over 1 m above ground level

Nevertheless, in chapter 5, more attention is given to the feedback of the Fukushima accident on the Gen II and III reactors, since this may have a much greater impact in the short term.

In addition to this introduction the document consists of 5 chapters.

- In chapter 2 a brief description of the Fukushima accident is summarized and an overview of challenges identified during the accident is given.
- Chapter 3 makes reference to other international activities and documents issued and summarises the lessons learned from the accident for several areas. Lessons from the European stress tests, which are relevant for various R&D areas, are also given here.
- Chapter 4 contains proposals for 13 research areas identified by the Task Group, as a reflection of the lessons learned from the Fukushima accident as discussed in chapter 3.
- Chapter 5 discusses cross-reference of newly proposed R&D activities to other SNETP target research areas.
- Finally, chapter 6 summarizes main conclusions of this report.

2. Overview of challenges identified during Fukushima accident

■ 2.1 The Fukushima site

Fukushima Dai-ichi NPP is located in the Northern region of Japan, in the Futaba County, Fukushima Prefecture, facing the Pacific Ocean on the east side about 300 km north-east of Tokyo. The site, operated by the Tokyo Electric Power Company TEPCO, hosts 6 nuclear units and a spent fuel storage pool as well. Unit 1 has a BWR3 reactor and MARK-1 containment, Units 2, 3 and 4 are BWR4 MARK-1, Unit 5 is a BWR5 MARK-1 and Unit 6 is a BWR5 MARK-2. The nominal electrical power of the reactors in the Fukushima site is 460 MWe for Unit 1, 784 MWe for Units 2-5 and 1100 MWe for Unit 6. When the earthquake struck Japan, at 2:46 p.m. JST (Japan Standard Time) on 11 March 2011, reactors 1, 2 and 3 were in full operation, while reactors 4, 5 and 6 were at shut-down.



Figure 3 - Fukushima Dai-ichi NPP

■ 2.2 Accident scenario for reactors 1, 2 and 3

The extremely strong earthquake - close to level 9 on the Richter scale (100 MSK-64) - had its epicentre in the sea, about 100 km offshore from the Fukushima site. It caused a sudden total loss of almost all the off-site power supplies. Reactors 1, 2 and 3, which were in full operation, were automatically shut-

down by control rod insertion. The residual heat removal systems were started immediately after, relying on electricity supplied by emergency power sources (diesel generators and batteries).

The Japanese tsunami alert system was activated very quickly. However, less than one hour later the first earthquake strike, the Fukushima site installations were flooded by a tsunami wave twice as high as the maximum provisional value considered by TEPCO in its risk re-evaluation carried out in the year 2000, and more than three times higher than the value predicted by the tsunami alert.

The wave flooded the emergency power generators and destroyed the pumping stations thus preventing the reactors and the fuel storage pools from being cooled normally. Nevertheless, cooling of the reactors continued to different extents and by different means for several hours through the emergency cooling systems, i.e.:

- In Reactor 1, through the Isolation Condenser (IC), which is able to condense the vapour from the reactor coolant system and inject it back to the system, thereby establishing heat removal by natural circulation. The High Pressure Core Injection (HPCI) System, which is designed to provide water through the annular torus and/or the storage pool, was unable to operate. TEPCO tried supplying water to the core cooling system via fire pumps, but their efficiency turned out to be quite low, possibly because some valves were stuck in the wrong position.
- In Reactor 2, the HPCI System was failing too, but the cooling water was supplied until 1:30 p.m. March 14 through the Reactor Core Isolation Cooling (RCIC) System, operating through a turbo-pump fed by the core outlet vapour.
- In Reactor 3, both emergency cooling systems remained operational for several hours; the RCIC provided the core cooling until 11:36 March 12, when it shut-down; supplementary cooling was ensured by the HPCI, which remained operational until 2:42, on March 13.

All emergency cooling systems were progressively lost for different reasons, so that none of them was in operation by the afternoon March 14.

The system deficiencies which caused the loss of the emergency cooling system are difficult to assess, as reliable information from the site is still missing. Even, the circumstances which prevented the operators from actuating injection of cold water from outside the site (the sea, for instance) to cool the reactor vessels down still remain undisclosed¹. Anyway, according to current knowledge, the efficiency and reliability of the decision making process during this extreme event was clearly not optimal.

When the cooling was lost, the residual power to be removed was estimated to be in the range 5 to 10 MW per reactor, which required supplying approximately 5 to 10 m³/h of fresh water to each reactor. The water in the reactor started vaporizing, which led to a sudden pressure increase and caused the venting of vapour into the suppression pool (wet-well), located in the annular torus. This is designed to be cooled down under emergency conditions through a heat exchanger, which unfortunately was not operating because the heat sink had been lost. The extensive vaporisation caused a reduction of the water level in the core, which quite quickly reached the threshold for clad rupture (estimated to be about 2/3 of the fuel assembly height)².

Several depressurisation operations of the containments were carried out when the core degradation had already started. Consequently,

large amounts of hydrogen were released outside the reactor containments, which resulted in violent explosions within the reactor buildings³. These explosions partially destroyed the buildings and also affected the fuel storage pool facility. The detonations damaged the Reactor 1 building first, then the Reactor 3, and they are most likely to have caused damage to the Reactor 2 torus.

Despite the extreme conditions due to the very high radioactivity levels, the operators eventually succeeded in injecting water from the sea into the vessels of the reactors, through the fire pumps, which contributed to stabilising the situation.

Until the connection to an external power source was restored, 11 days after the initiating event on March 22, all the attempts to recover the electrical supply from outside the site failed, mainly due to electrical control panel short-circuiting.

Fresh water has been continuously injected into the reactor cores since May 25.

On March 25, the operators discovered large amounts of contaminated water in the basements of the turbine buildings⁴. The handling of this contaminated water and the liquid radioactive waste remained one of the major concerns on the site. Many efforts have been made by TEPCO including use of storage tanks for the contaminated water and installation of decontamination units.

This document does not deal in detail with broad activities on reconstruction of the accident

1 - Actually, the vessel material was quite old and the embrittlement could have been significant.

2 - It is remembered that the LWR fuel clad starts deteriorating at about 800 °C, then potentially breaks out; eventually the fuel starts melting at around 2300 °C through eutectic interactions. In Fukushima, the oxidation reaction of the claddings at high temperature under the action of the water produced large amounts of zirconium oxide and hydrogen, which mixed with vapour and built-up in the uppermost region of the principal cooling circuit, then within the containment. The chemical reaction was accelerated by the temperature increase in particular when the temperature exceeded 1200 °C. As much as 50% more hydrogen could have been delivered, compared to conventional PWRs, as a consequence of the large amount of zirconium due to the fuel assembly design.

3 - During the fuel degradation, the production of hydrogen has been coupled with the emission of volatile fission products. Thus the venting released to the environment large amounts of volatile products, such as the noble gases, the iodine - in gas form -, and aerosols, including Caesium 137. Luckily, part of the contaminants had been trapped in the wet-well, so reducing the environmental contamination.

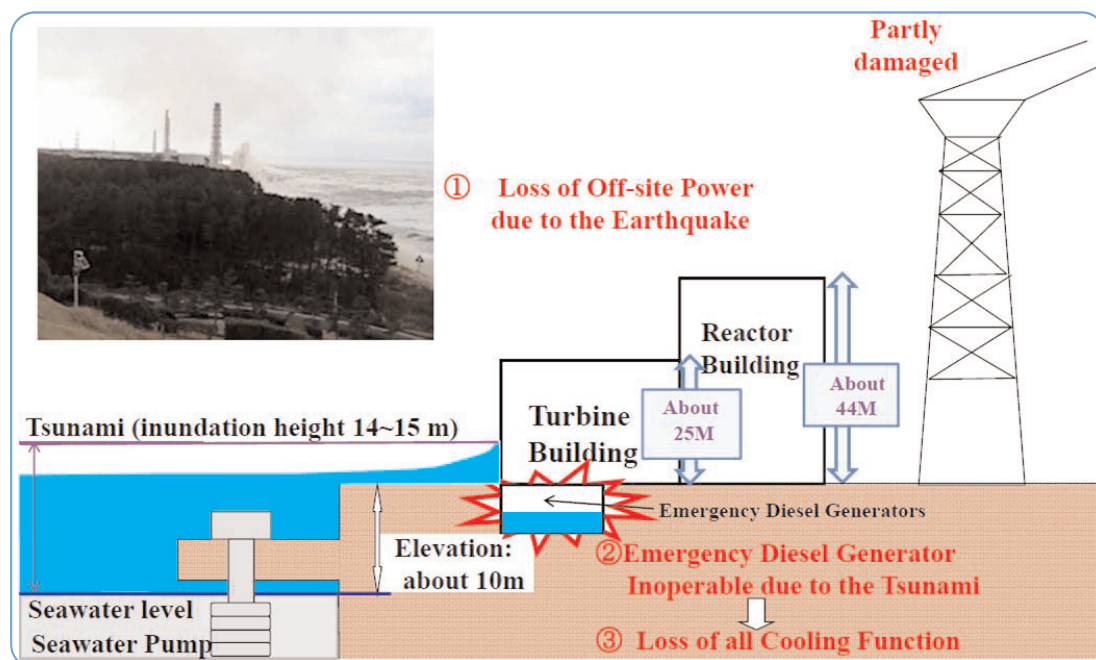


Figure 4 - Causes of the accident and plant damages

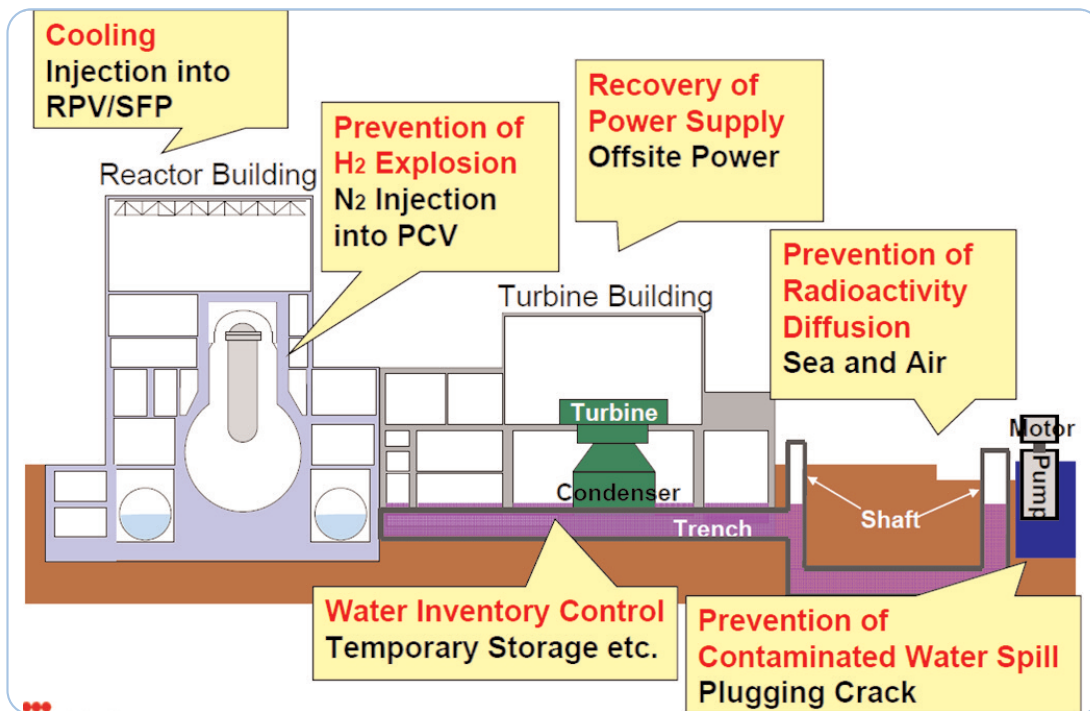


Figure 5 - Recovery actions

scenario, which have been carried-out, and are still ongoing, because of limited information available up to now. Nevertheless it should be underlined that all activities aimed at an investigation of the phenomenology of the events and available data are extremely important to enhance the knowledge and improve the reliability of computation through validation, especially for the severe accidents simulation tools.

■ 2.3 Spent fuel pools

When the accident happened, the fuel storage pool of reactor 4 - which had been shut-down since December 2010 for maintenance operations - had got the maximum load with 3 full cores, including the just unloaded one.



Figure 6 : Motor of fuel loading machine in spent fuel pool (source "TEPCO, WNN")

On March 15, a series of events - either fires or hydrogen fast combustion (deflagrations) - affected the Reactor 4 building and caused serious structural damage. According to current evaluations, these events could not have originated from either thermal or neutronics events in the pool⁵.

Several assumptions have been made to explain these deflagrations, although all of them require further confirmation. Two of the main ones not directly related to the event in the pools were:

- The build-up of hydrogen originating from Reactor 3 through the existing connections, because the two plants share the same stack⁶.
- The rupture of a hydrogen circuit in the reactor building as a direct consequence of the earthquake.

Other assumptions more directly linked to the pools include:

- The locally ineffective venting and cooling down - due to work degradation - which could have contributed to building up hydrogen pockets originating from radiolysis in the pool⁷.
- The large production of hydrogen as a consequence of insufficient cooling and fuel degradation.

According to in-situ inspections (through films, water radioactivity monitoring, etc), it is now widely acknowledged that no significant fuel degradation occurred in the Reactor 4 storage pool, which supports the explanations relying on outside originating events. The temperature of the water in the Reactor 4 fuel storage pool was

4 - The sea water originally entered into the basement of the Reactor 4 building, as a direct consequence of the tsunami flooding. It has been later contaminated through injection of water from the reactor containment. In the case of Reactor 2, the leakage probably originated from the failures in the torus, damaged by the March 15 explosion. The strong contamination demonstrates the efficiency of the pools to mitigate the air releases.

5 - Considering the loading and the fuel burn-up, the overall residual heat in the fuel pool of reactor 4 has been evaluated ex-post at about 3 MWth. Accordingly, accounting for the large thermal inertia and the initial water level, the coolant temperature should not have reached the boiling threshold before one/two days after the initiating event. Thus some experts claim that the first assembly heads could have started uncovering on March 18, at the earliest. This position is not unanimously shared. Moreover, Japanese recently provided experimental evidence to counter it.

6 - Further experimental evidence has been provided later on, which strongly supports this explanation. Actually, analysis of the activity levels of the differential air filters demonstrated a one-directional hydrogen flow from Unit 3 to Unit 4.

7 - This position is not widely shared based on the claim that the radiolysis could not be able to produce such large amounts of hydrogen.

rising until a complementary cooling capacity was provided (e.g. for Reactor 3 pool through helicopter supply, from March 17 and later on by fire truck). In the case of Reactor 4 fuel pool on March 20, the supply of water was first provided through a water hose and then through a concrete duct from above through an articulated arm.

From then on an additional continuous supply has been necessary to compensate for evaporation and leakage. Luckily, the civil works have accommodated the combustion and deflagration of hydrogen without any major consequence. Nevertheless, it is obvious that, had a severe degradation of the fuel happened, the situation would have deteriorated quite quickly, thus causing large early releases to the environment.

■ 2.4 Fukushima radiological issues

The incumbent risk of core melting was recognised very quickly, as a consequence of the possible failure of water injection, even if precise information on the availability and the operability of core cooling systems on each unit was missing. Before the explosion of the Unit 1 building, none of the environmental radioactivity measurements identified large releases, even after the first venting of the Unit 1 containment. Nevertheless, the severity of the situation in case

of a long-lasting blackout was promptly realised. The following issues and necessary, urgent actions were identified to protect the plants:

- The primary circuit had to be discharged into the reactor containment via the suppression pool to control the pressure. Cold water injection could have prevented a fast increase of the containment pressure.
- Without actuation of the emergency cooling, the water in the suppression pool would have progressively warmed-up and started boiling.
- The reactor containment pressure would have increased quickly because of the very small size of the containment, compared to PWRs.
- The containment should have been vented periodically to avoid rupture.
- In case of core dewatering and melt, the contaminants would have been released from the fuel to the primary circuit, then to the reactor containment through the suppression pool and eventually partially released to the environment via the containment venting line (if any).
- The large amount of hydrogen produced by the clad oxidation during the melting would have caused a very high risk of hydrogen combustion in the reactor building in case of leakage from the containment vessel.
- The hydrogen combustion inside the secondary containment could have damaged the structures, jeopardized the pool structures, destroyed the roof and created a bypass to the turbine hall.
- Publicly available calculations were predicting very high release in such conditions.

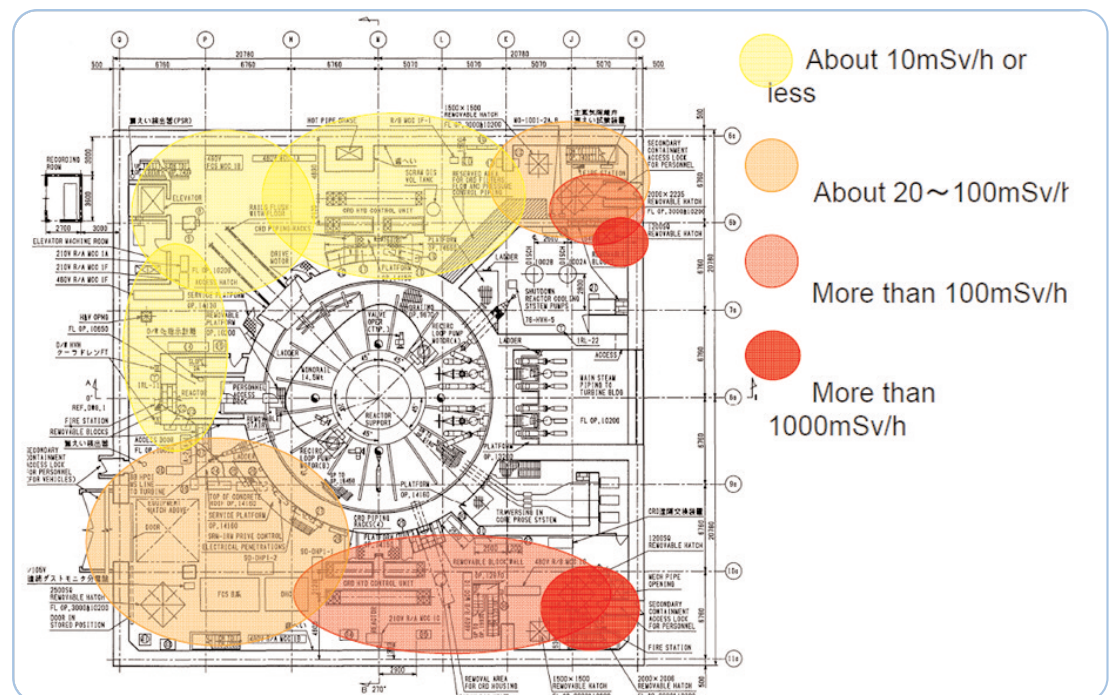


Figure 7 - Radioactivity release and radiation levels



The assessment of the radiological conditions can be described based on documents [1-4]. The explosion of Unit 1 on March 12, 15:36, was quickly identified as a hydrogen explosion. That provided evidence that the core had already started melting. It was therefore obvious that part of the gaseous radioactive elements (noble gas, iodine) had already spread out in the environment. The explosions in Unit 2 & 3 buildings definitely demonstrated how dramatic the sequence of events for these plants could be, in case of long-term station black-out.

The early atmospheric releases were transported towards the north and then towards the ocean. Most of the meteorological stations and the dose rate measurement stations were out of use during this period. The only station which was able to detect the radioactive plume from Unit 1 was the Minami Soma one, located on the shore approximately 25 kilometres north of the nuclear site.

period of rain occurred from 9 p.m. to midnight. The consequential wash-out of the radioactive plume produced a large deposition in the environment.

The Tokyo area was impacted mainly by the releases from Unit 2. The high dose rate area first spread to the southern region of Fukushima, towards Tokyo and then moved towards the north-west in the direction of Fukushima city and Itate.

Unexplained atmospheric releases were observed from March 19. The releases were transported first towards the north-west, then directly to the ocean. During the night of March 20, a large-scale meteorological circulation transported fission products which were over the ocean, and then back towards Japan. From March 21 the Tokyo area was affected again with at least three days of rain in the area. The combination of rain and fission products in the atmosphere led to contamination of the Tokyo area. (See figure below)

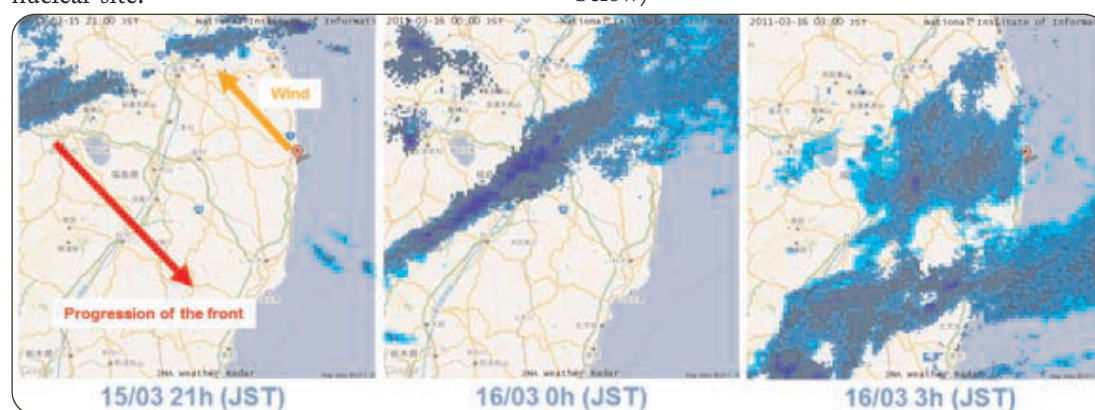


Figure 8 - Meteorological conditions March 15th and 16th

Within a domain of dozens of kilometres, the major contamination of the environment originated from the releases from Unit 2, the core of which had already started melting on March 14, followed by the resulting explosion in the torus room of the primary containment vessel, on March 15.

This event and the subsequent venting operations from midnight March 15 onwards engendered massive atmospheric releases too, which initially went south, then progressively switched to the west and finally to north-west as the wind direction changed. Consequently a wide area westward of the site was impacted by atmospheric releases from Unit 2.

Shortly after 8 p.m., heavy rain started moving from the north-west towards the site (in the opposite direction of the plume). The major

■ 2.5 The current situation in Fukushima and recovery activities

The exact extent of the damage in the Fukushima reactors it not yet known since it is impossible to directly observe the pressure vessel and the primary containment. This is only expected to be possible several years from now. However, according to simulations performed by TEPCO on the basis of the sequence of the events and of the released radioactivity [5], it is assumed that the corium was able to melt through the Reactor Pressure Vessel (RPV) in Unit 1, while it is expected to have been retained inside the RPV in Units 2 and 3. The estimation of radioactivity release given by the Japanese government in June 2011 was about 15% of the Chernobyl

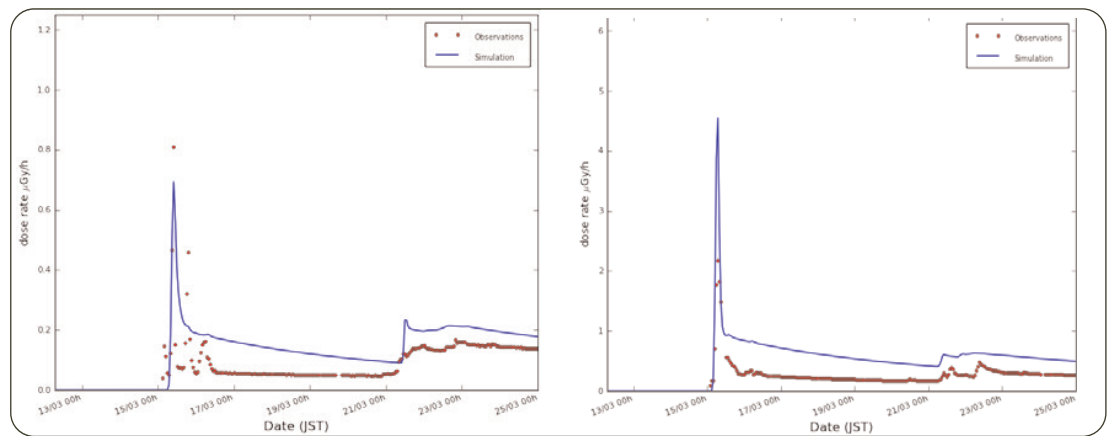


Figure 9 - Dose rate comparisons - Tokyo city centre (a) and in Hitachi miya (b) - Source REF.4

release; this value is questionable, however no updated official estimations are available.

On December 16, 2011, the plant was officially declared in a state of “cold shutdown”. A reasonable interpretation of this statement is that the core and corium debris were being stably cooled, and that the coolant pressure and temperature were low and under control. A stable cooling condition was achieved also for the spent fuel pools, by installation of dedicated heat exchangers and devices for maintaining the water level.

The contaminated debris outside the buildings have been removed and stored in containers. The radioactivity emissions have decreased to an acceptable level and the dose rate level on the site boundary is between 10 and 100 μ Sv/h. However inside reactor buildings the radiation level varies from about 10 mSv/h to more than 1 Sv/h. A lot of debris is still there and part of it has high radiation dose rate. Dose maps have been compiled and attention is devoted to reduce worker exposure during works on the site, with the installation of dedicated facilities for hosting them on the site and for improving the health care.

Several actions have been performed and are ongoing to prevent further contamination. The covering of Unit 1 has been completed. Inhibitors have been sprayed to prevent spreading of radioactive dust. Support structures have been installed at the bottom of the spent fuel pool in Unit 4. A temporary barrier has been installed as a countermeasure against tsunamis and a water shielding wall is under construction to prevent underground water leakage towards the ocean.

According to the medium-long term decommissioning plan, fuel removal from the spent fuel pools is expected to start in two years and removal of fuel debris from the reactors in ten years, with completion in 25 to 30 years.

During this period, several development actions will be required to support the decontamination and decommissioning activities. A list of these actions has already been identified by TEPCO:

- Development of inspection methods and devices for inspection of leakage points in the containment vessel, and for operation in high-temperature, high humidity and high-dose environments.
- Development of remote sampling and decontamination methods.
- Development of technologies and methods to repair leakage points, including underwater repair.
- Development of systems to prevent the dispersal of radioactive materials.

Also the technologies for core defueling and fuel debris removal will have to be improved compared to the previous experience in TMI, since in the case of TMI there was no fuel in the containment. Finally it will be necessary to develop technologies for managing and treating radioactive waste which do not belong to the present waste categories. A hot laboratory will have to be installed on the site since it is expected that the decontamination and fuel debris removal will generate non-transportable samples. Specific methods for waste treatment, packaging, storage and disposal will likely be necessary.



Figure 10 - Decontamination using synthetic resin emulsion (source “TEPCO, WNN”)

3. Lessons learned from the Fukushima accident

■ 3.1 Overview of Fukushima Lessons in Major International Activities and Documents

As was the case for reactor accidents in the past, after the Fukushima event the nuclear industry reacted promptly to identify areas for safety improvements. This process started at the level of each individual organisation, but very soon efforts have been coordinated at international level in order to develop a shared vision of what happened and what implications it has for the future.

This section provides a short review of a limited number of relevant documents and meeting outcomes, representing the view of different institutions:

1. The IAEA expert mission report [6].
2. The Japan government report [7].
3. The Near Term U S Nuclear Regulatory Commission report [8].
4. The OECD/NEA Forum on Fukushima accident; this was actually a meeting of the NEA Committee on Nuclear Regulatory Activities (CNRA) [9].
5. The ETSON position paper on research needs for GEN 2 and GEN 3 NNPs [10].
6. The IRSN Special report on Fukushima [11].
7. The IAEA International Experts' Meeting on Reactor and Spent Fuel Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, March 19-22, 2012 [12].
8. The report of the Fukushima Nuclear Accident Independent Investigation Commission (NAIIC), established by the National Diet of Japan [13].

Most documents have no explicit suggestions for R&D programmes, but they provide with the general framework allowing identification of the R&D topics with the highest priority. In addition some of them also give explicit

indications for R&D directions, for example the ETSON report [10]. A short description of the content and the most relevant conclusions of the documents is provided below.

3.1.1 The IAEA expert mission report

The IAEA expert mission in Japan from May 24 to June 2, 2011 led to the issuing of an important report, which influenced all actions launched at international and European level to assess and to further enhance the safety of nuclear installations. The report's findings were presented at a ministerial conference in Vienna from 20 to 24 June, with the aim of providing initial information about the accident, assessing the level of emergency preparedness at the international level, in order to reinforce and discuss the implications of the incident for the safety of all nuclear facilities, identifying any areas to be reviewed, lessons learned and future actions.

The report includes the following parts:

- a) A reconstruction of the accident sequences. This part has been superseded by more detailed documents issued later, for instance the INPO report [14].
- b) A series of 15 conclusions, derived from the IAEA Fundamental Safety Principles. The main finding is that IAEA Fundamental Safety Principles provide a robust basis in relation to the circumstances of the Fukushima accident and cover all the areas of lessons learned from the accident. In Fukushima there were insufficient defence-in-depth provisions against tsunami hazards, and accident management provisions were not adequate to cope with severe accidents in general and with multiple plant failures in particular. The report suggests that a periodic updating of national regulations and guidance to internationally established standards and guidance should be considered. In addition a

review of the IAEA Safety Standards in order to cover multi-unit sites may be advisable.

c) **Lessons learned. Sixteen lessons grouped into four areas were identified, generally applicable for all operators of NPPs:**

- nuclear system organization, safety infrastructure and safety culture,
- assessment of risk from external events and prevention measures,
- phenomenology, management and mitigation of severe accidents,
- emergency preparedness and management.

The main issues identified in the report were:

- when evaluating the risk from extreme external events, it is important to pay careful attention to possible cliff edge effects, which require a specific safety approach, because they can widely overrun the safety margins, thus engendering very detrimental potential consequences, despite their very low probability. This topic should be addressed considering the occurrence of a fully-new class of probabilistically negligible, but potentially extremely damaging situations,
- for accident management it is necessary to take the right decisions in due time; the Fukushima experience has shown that the decision processes appropriate for normal operation may be inadequate during emergencies,
- the emergency and evacuation plans should be considered not only for the first phase of the accident, but should be comprehensive in order to ensure the health of the population in the medium and long term.

3.1.2 The report of the Japanese government.

The report issued by the Investigation Committee established by the Japanese government, has a very wide scope.

It includes an overview of the nuclear regulatory system in Japan, a detailed assessment of the external events (earthquake and tsunami) with their impact on the Fukushima plant and of the accident evolution. It also investigates how the emergency was managed and evaluates what amount of radioactive materials was released to the environment and the level of radiation exposure. It also discusses the co-operation with international institutions and foreign organisations, how communication was managed and the expected future remediation work.

A detailed list of 28 lessons was generated. Some of these lessons are specific to Japan, in particular those dealing with the regulatory independence, which in the Japan nuclear system was not fully guaranteed. Other lessons are related to issues applicable and already considered in most nuclear countries. Probably the most interesting lessons for the whole community are those addressing the issue of emergency preparedness and management, since Japan is assumed to be one of the best prepared countries for natural disasters.

3.1.3 The NRC Near Term Report

Soon after the accident, NRC constituted a Task Force which issued on July 12th, 2011 a “Near Term” report [8] containing a series of recommendations. These are mainly addressed to NRC itself, suggesting improvements in the regulatory framework in order to enhance the safety level of US nuclear reactors. Similar to the IAEA lessons, these recommendations are mainly dealing with the strengthening of the mitigation capability in case of severe accidents, especially in case of multi-unit sites, and with the enhancement of the preparedness to manage unexpected situations.

Similarly to the situation in Europe, US licensees are requested to re-evaluate and upgrade as necessary the seismic and flooding protection for all operating reactors. A regulatory system based on balanced risk-informed and deterministic defence-in-depth approach should be maintained and strengthened.

3.1.4 The CNRA Forum on the Fukushima Accident

The OECD/NEA Committee for Nuclear Regulatory Activities met in Paris on June 8, 2011. The Forum noted that after Fukushima, in-depth assessments of plant safety had already been carried out by many regulatory authorities in NEA member states and associated countries, and invited remaining regulatory authorities responsible for the oversight of nuclear installations to launch similar reviews and analyses as soon as possible.

The Forum also declared its commitment to systematically advance the knowledge needed for plant designs and post-accident situations. The identified priority areas include extreme



external natural hazards and resistance against these hazards and combined events, ability of safety systems to withstand severe accidents, emergency response and management capabilities, crisis communication and site recovery plans and their implementation.

Overall, the Forum underlined the importance of co-ordinated and comprehensive actions by all regulatory authorities.

3.1.5 The ETSO position paper

This document - the development of which had already started before the Fukushima event - had the more general purpose to contribute to the SNETP project definition and launching, by identifying research priorities for GEN II and III reactors, with specific focus on safety research. Nevertheless, the Fukushima event - which occurred during the final stage of the preparation - has unavoidably strongly influenced the document.

The ETSO position paper includes an appendix dedicated to the Fukushima accident. There the paper identifies some lessons learned, in particular in the field of crisis management and lists a series of possible improvements in safety methodologies. The appendix provides specific indications for future research, in order to address the following requirements:

- To evaluate in the best estimate way the behaviour of the plant systems for beyond design basis accidents.
- To evaluate the ultimate capacity of the systems with respect to the load applied and to identify when the level of damage becomes non-linear or catastrophic.

These objectives may require a large extension of physical modelling and computer tool development in different areas and in particular in the area of severe accidents and containment system simulation.

The paper also includes a series of suggestions for research submitted by JNES, the Japanese TSO, specifically addressing improving the knowledge of the Fukushima accident, its environmental impact and to support the site restoration process.

3.1.6 The IRSN Special report

IRSN dedicated the full January 2012 issue of their Repères Magazine to the Fukushima accident and the lessons learned.

In the editorial paper, IRSN announced the will to promote the concept of “hardened core safety” at the international level. This is based on “an additional level of safety-in-depth at nuclear facilities to ensure that their vital safety functions remain operational over a sufficient period of time in the event of any physically possible environmental hazard”.

As far as research is concerned, the issues identified by IRSN are:

- Better characterisation of natural events, like earthquakes, floods, etc., including methodologies for dealing with rare events.
- Protection of persons and the environment, including better and faster environmental monitoring, better models for contamination predictions, health effects of low doses, and effect of contamination on the environment – in particular the marine environment.
- Broader consideration of social sciences, both at facility level and outside the boundary of the plant.

3.1.7 The IAEA Expert Meeting, March 2012

During the IAEA International Experts Meeting on Reactor and Spent Fuel Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, held in Vienna on March 19-22, 2012, all the relevant technical aspects of reactor and spent fuel safety in light of the Fukushima accident were discussed, tackling the results of several national assessments of vulnerability of their NPPs. In some of these studies the IAEA's complementary methodology released in November 2011, was applied.

The meeting showed that the effort of the Member States and the IAEA was comprehensive and thoughtful, and that good progress in improving safety has been made. From the R&D point of view, it has to be mentioned that experts also proposed the undertaking of further research about the phenomenology that characterises the accident progress.

3.1.8 The report of the NAI Commission (National Diet of Japan)

This report lists several errors and signs of negligence that made the Fukushima plant unprepared for the events of March 11, identifying deficiencies and failures in the

response to the accident by TEPCO, the regulator and the government.

The Commission identifies as the main cause of the accident the conventions existing in Japanese culture and mindset: the attitude to the obedience, the reluctance to question the authority, the devotion to the company or to the “group”. It underlines the lack of a clear identification of the responsibilities of the regulator and of the promoters of the nuclear energy, as well as the lack of control of the civil society over the nuclear institutions.

The Commission also ascribes to TEPCO organisational problems, identifies shortcomings in the law and regulations, and spurs for no cosmetic solutions.

■ 3.2 Lessons drawn on enhancement of safety infrastructure and culture

The different outcomes from Fukushima events investigations support several recommendations to improve the current safety assessment methodology and policies, such as:

- Agreeing internationally on major safety objectives, e.g. through WENRA reference levels and safety objectives;
- Searching for a common design certification, through extending and generalising the current MDEP (Multinational Design Evaluation Program) process and gathering together regulatory bodies and technical safety organisations;
- Adopting a common policy to support only certified designs on the international markets, whilst protecting the intellectual property of the designs;
- Generalising the scope and the practice of the stress-tests worldwide;
- Searching for harmonisation of the assessment practices and methodologies;
- Defining standards for competence evaluation in the reactor safety field;
- For current and advanced reactor designs, extending the defence-in-depth application to any aggression source, both internal and external, including the beyond design basis events either to exclude, if they are likely to lead to early radioactive releases, or at least to mitigate their environmental impact;

- as far as the Gen IV reactor concepts are concerned, strictly applying the generalised exclusion principle that claims the absence of any technical need to evacuate the population neighbouring the reactor site.

■ 3.3 Lessons drawn on plant design and on evaluation of external hazards

The Fukushima accident was triggered by the combination of two main initiating events - an exceptional magnitude earthquake and the associated tsunami wave - that struck a site which already suffered from severe weather conditions (cold weather with icy climate and snow). The combination of these three agents led to:

- The loss of almost all the off-site power supplies;
- The flooding of the site by a wave twice the size of that considered in the year 2000 risk evaluation, which led to both the loss of all the emergency power supply system and the ultimate heat sink;
- The build-up of civil structures debris, which under the effect of the massive damage caused by the tsunami and the severe weather conditions, combined with the radioactivity, prevented the site from being effectively accessed on the ground;
- The situation affected all reactors on the same site; it could have also affected some other sites (especially Fukushima Dai-ni).

The combined effects infer that the following aspects need to be considered:

- Extending even further the in-depth safety approach to any type of hazards, in particular external ones, and accounting for any mode of combination of them;
- Systematically including the design extension conditions (beyond design basis accidents) in the defence-in-depth approach at the design stage;
- Developing wider and more robust lines of defence with respect to the design basis;
- Including systematically in the in-depth safety approach the situations where several plants on the same site are affected by a beyond design basis event;
- Taking into account in the design of additional measures for beyond design basis events, where several nuclear sites are concerned and communication means (e.g. roads) are severely degraded.



■ 3.4 Lessons drawn on mitigation of severe accidents

Severe accidents were not prescribed as safety design basis for current plants and they are not even considered in full scope for Gen III plants in some countries. Severe accident protection has been taken into account through “ad hoc” rules, addressed to help operators in managing hydrogen releases, prolonged station black-outs, anticipated transients without scram (ATWS) and others possible sequences. Nevertheless, severe accidents are considered for existing plants as design extension conditions (beyond design basis accidents).

The execution of several experimental programmes has significantly increased the knowledge about phenomena which may occur in design extension conditions. The execution of level-2 PSA for many LWR plants and the analysis of several sequences using up to date codes like MAAP, ASTEC and MELCOR, provided very good insights into plant behaviour and helped in developing severe accident management procedures.

Nonetheless, the work performed till now did not allow for sufficiently detailed simulation of the course of Fukushima accident, including evaluation of the source term after the loss of the relevant infrastructures. It is therefore very important that the future research in this field be accompanied by a parallel effort to transfer the enhanced knowledge into actual improvements of operating plants and to really protect the public against a low probability high consequence severe accident, which cannot be completely excluded to occur in a LWR plant.

Some items to be considered with priority are:

- Provide simple alternative power sources (such as mobile power, compressed air and water supplies), ensure available essential safety related parameters based on hardened instrumentation and secure communication lines for control rooms, emergency centres and other places on and off-site.
- Strengthen and integrate on-site emergency response capabilities, ensure an adequate number of experienced personnel who can deal with each type of reactor and can be called upon to support the affected sites, enhance the training for responding to severe accidents.
- Revise the risk and implications of hydrogen explosions, enhance the measures to prevent them

and implement mitigating systems, including hardened containment venting arrangements.

- Enhance spent fuel pool makeup capability and instrumentation for the spent fuel pool.

Last, but not least, modification of the reactor design should be considered, which would include feeding the primary circuits of NPPs, through additional nozzles in the main coolant system. These design modifications could be defined based on PSA results within a risk-informed overall approach. It should be carefully checked, that additional measures would not result in increased risk due to large complexity of the design or use of unproven design solutions.

■ 3.5 Lessons drawn on the emergency preparedness and management

The main difficulties and drawbacks in the management of the Fukushima accident came from:

- The concomitance and overlapping of many non-nuclear and nuclear events. The effects of both the earthquake and the tsunami on the survival and living conditions of the population in the surrounding regions attracted the prime attention of the authorities and officials at the very early stage of the crisis.
- The complexity and difficulty of the decision making process which affected the effectiveness and promptness of the actions and generated both confusion and delays.
- The location and lay-out of the site, the severe environmental conditions and the build-up of debris consequent to the earthquake and tsunami devastation, which prevented intervention from the ground, e.g. to replace the failing generators or perform a successful change of shift (possibility of shift members affected by the disaster while not on duty).
- The simultaneity of the aggression on several units and their pools on the site, the status of each one of them continuously impacting the others, and vice versa, and sometimes preventing the workers from intervening.
- The practical impossibility to efficiently and durably recover a suitable and stable electrical supply source.

It is now widely agreed that the involvement of several units and reactor fuel pools in the crisis management situation created unacceptable levels

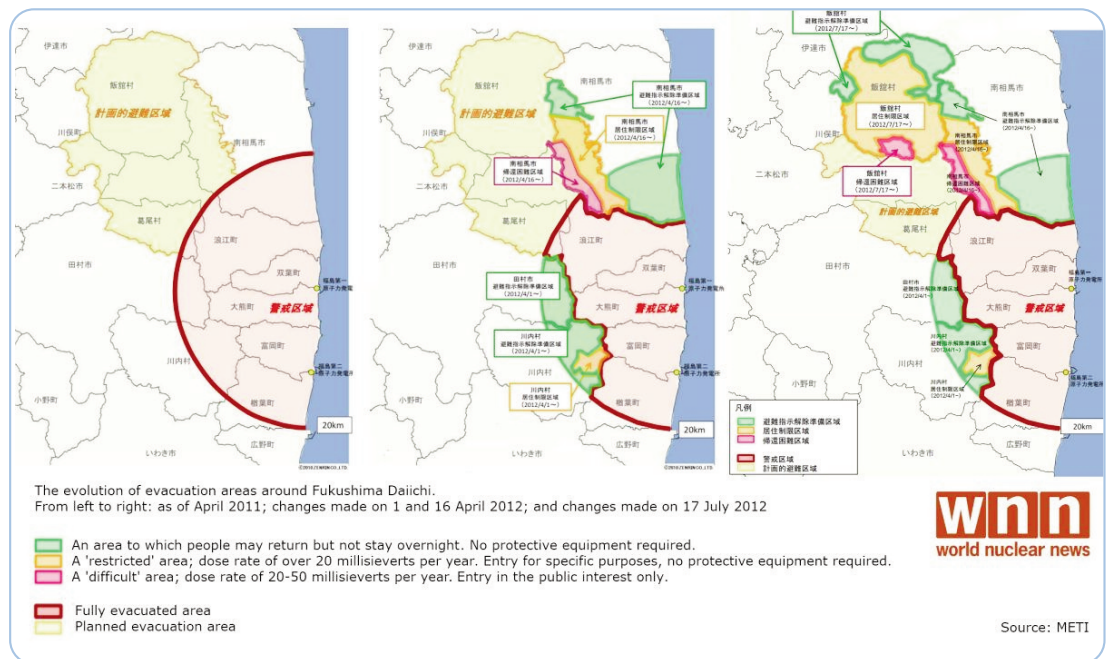


Figure 11 - Source : METI, WNN

of stress for the operators, already affected by the extreme working conditions and the extended lack of communication with their families and relatives which added to the stress. The human factor has turned out to be a fundamental issue in the Fukushima crisis management. Specific training in abnormal and extreme situation management of qualified intervention groups (including e.g. military troops) has been advocated to address these issues.

International collaboration can also effectively help. Any country affected by such a huge catastrophe should be allowed to seek help and support from neighbouring countries. Nevertheless to be effective, this support should not conflict with national emergency practices. Accordingly, harmonisation of practices for emergency management should be undertaken worldwide to achieve enough uniformity and standardisation in organisation, technical communication, management methodologies, data acquisition methodologies and tools. That could also help to overcome the practical barriers such as language, knowledge, and familiarity with the design..

In the case of a major emergency the international experts, beyond direct involvement in the national organisation, could provide help from abroad using long distance communication on plant status diagnosis, prognosis of the accident progression and on selection of the management strategy, provided that the necessary organisation has been set up.

Moreover, the Fukushima events indicated that emergency management means should preferably be independent for each unit at a site, and also sufficiently robust to cope with the local weather and access conditions. This underlines the usefulness of relying on the availability of redundant intervention means in the vicinity of the site.

Some items to be considered with priority in the future are:

- Requiring that facility emergency plans address prolonged station blackout and multiunit events.
- Organising large scale radiation protection for workers on the site under severe accident conditions.
- Improving and refining the existing methods and models to determine the source term, accurately predict the effect of released radioactive materials and clearly define the criteria for wide-area evacuation.
- Pursuing emergency preparedness, reinforcing the environmental monitoring, clarifying the allocation of roles between central & local organisations in responding to the combined situation of a massive natural disaster and a nuclear emergency.
- Assessing the concept of long term sheltering in favour of the concepts of 'deliberate evacuation' and 'evacuation-prepared area'.
- Enhancing communication to domestic and international communities regarding the accident;
- Establishing an internationally shared approach to emergency management, allowing effective assistance from other countries.



■ 3.6 Outcome of the stress-tests and R&D implication

Following the Fukushima Dai-ichi accident, the European Council of 24-25 March 2011 requested that a comprehensive safety assessment were performed on all EU nuclear plants, in light of the preliminary lessons learned. The request of the Council included stress tests performed at national level, complemented by a European peer review. Consensus on specifications of the stress tests was achieved by ENSREG and the European Commission on 24 May 2011. This multilateral exercise of the stress tests covered over 150 reactors in European countries operating NPPs. The stress tests and their peer review focused on three topics:

- 1) Natural initiating events, including earthquake, flooding and extreme weather.
- 2) The loss of safety systems.
- 3) Severe accident management.

The 15 European Union countries with NPPs as well as Switzerland and Ukraine performed the stress tests and were subjected to the peer review. The stress tests and peer review consisted of three steps. In the first step the plant operators performed an assessment and made proposals for safety improvements, following the ENSREG specifications. In the second step the national regulators performed an independent review of the operators' assessments and issued additional requirements. The last step was a European peer review of the national reports submitted by the regulators. The peer review, which started on the 1st of January 2012 consisted of a desktop review (study of submitted national report), followed by a two week assessment of the report during topical review, completed by additional discussions during the country reviews. There were about 80 reviewers from 24 European countries participating in the peer review. Observers from several non-EU countries (Canada, Croatia, Japan, UAE and USA) as well as the IAEA also attended.

As a result of the stress tests 17 national reports, a peer review report for each of the seventeen participating countries, and a final peer review report (developed by the Stress Test Peer Review Board and endorsed by ENSREG on 25 April 2012) were produced [15]. The review focused on the identification of strong features,

weaknesses and possible ways to increase plant robustness in light of the preliminary lessons learned from Fukushima.

Although the stress tests were based on information available at the time and were not primarily intended to specify areas for future research, they also indicated, explicitly or implicitly⁸, the need for future studies and development in the following areas:

a) Plant design and identification of external hazards

- Development of approaches to natural hazard definition, techniques and data, and development of guidance on natural hazards assessments, including earthquake, flooding and extreme weather conditions.
- Development of guidance on the assessment of margins beyond the design basis and cliff-edge effects for extreme natural hazards.
- Development of a systematic approach to extreme weather challenges and a more consistent understanding of the possible design mitigation measures.
- Development of the approach for assessment of the secondary effects of natural hazards, such as flood or fires arising as a result of seismic events.
- Enhancement of PSA for natural hazards other than seismic (in particular extreme weather) and development of methods to determine margins and identify potential plant improvements.
- Overall enhancement of PSA analysis, covering all plant states, external events and prolonged processes, for PSA levels 1 and 2.

b) Analysis of severe accidents

- Further detailed studies on progression of severe accidents, allowing the determination of the timing of cliff edges such as core melt, reactor pressure vessel failure, containment basement melt or other modes of containment failure, uncovering of spent fuel pool fuel.
- Further analysis of phenomena associated with reactor cavity flooding and related steam explosion risks following potential reactor vessel penetration by molten corium.
- Studies of long-term containment overpressurisation due to excessive production of steam and non-condensable gases, and means for protection of containment integrity, including filtered venting.

8 - The text below enumerates topics of R&D which are more or less derived from the lessons learned from the stress tests and the subsequent investigations carried-out in different countries. The text is more aimed at providing a relevant list of topics than making an explicit connection to the stress-test outcome.

- Studies of potential re-criticality both in reactor cores as well as spent fuel pools, taking into account potential geometry and material composition changes caused either by external hazards or by the progression of the severe accident.
- Further analysis of hydrogen production, distribution, deflagration and detonation in complex containment geometries.
- Analysis of potential for migration of hydrogen into spaces beyond where it is produced in the primary containment, as well as hydrogen production in spent fuel pools and of measures to reduce the hydrogen risk.
- Analysis of severe accidents involving molten fuel in the spent fuel pools and measures for mitigation of the consequences, including venting of buildings in case of coolant boiling in the spent fuel pools.
- Determination of expected radiological conditions inside plant buildings and outside during severe accidents, as well as the limitation of radiological releases, including situations with the damaged containment.

c) Management of severe accidents

- Development of advanced instrumentation based on simple physical principles (e.g. passive temperature, pressure readers) able to operate and being used specifically in station black-out and loss of DC power.
- Systematic evaluation of the availability of safety functions required for severe accident management under different circumstances.
- Feasibility of accident management actions for long processes with duration of several days, involving accidents occurring in parallel on several units, and taking into account potential interactions between the reactor core and the spent fuel pool.
- Investigation of cooling modes for partially relocated core prior to reactor vessel failure, including assessment of possible vessel failure due to thermal shocks in older NPPs.
- Further assessment of the feasibility of various strategies for molten corium cooling, both in-vessel as well as ex-vessel, aimed at protecting containment integrity.
- Enhancement of the methods and tools for severe accident management training and exercises, (such as desk-top training, use of multi-function or full-scope simulators) including development of new training tools for NPP staff training.

d) Emergency management and radiological impact

- Technical and organisational strengthening of on-site emergency arrangements, including on-site emergency centres protected against extreme natural hazards and contamination.
- Studies of the logistics of the external support and related arrangements (storage of equipment, equipment and manpower resources, use of national defence resources, etc.).
- Studies of feasibility of operations in the event of widespread damage, for example, following an earthquake, including the needs for different equipment (e. g. bulldozers) and plans on how to clear the route to the most critical locations or equipment.
- Enhancement of methods for assessment of radiological situations on site including the case of multi-unit accidents, in connection with radiation monitoring, habitability and feasibility of accident management actions.
- Development of conceptual solutions for post-accident fixing of contamination and the treatment of potentially large volumes of contaminated water.

■ 3.7 Impact on the R&D directions and priorities

Prior to Fukushima, the R&D activities related to existing reactors were predominantly focused on the issues associated with the long-term operation. While these issues remain equally important, great attention should be paid to safety. In the area of safety the main objectives of the R&D programmes for the reactors presently in operation and under construction are:

- On the one hand, appreciating and improving the operating and safety margins with respect to the design basis accidents.
- On the other hand, extending them to the beyond design basis situations, e.g. through the safety margin approach which relies on the definition of the risk space which accurately accounts for any kind of generating events.

Capitalising on the first evaluations and relying on the above mentioned considerations, it is today widely acknowledged that the Fukushima events do not require either major re-orientation of current R&D programmes or their



cancellation at national and international levels. It also means that the current SNETP objectives and content are only slightly challenged. In particular, the importance of the SARNET network to share effort on severe accident R&D as well as projects such as the ASAMPSA2 (best-practices for Level 2 PSA) is confirmed and should be continued with the objective to produce knowledge, methods and codes able to assess risks experienced by NPP for all beyond design situations. Nevertheless, careful investigation of the Fukushima event outcome is likely to engender a new scale of priority of programmes, with a particular focus on external extreme events and their combination, common mode effects and human behaviour. In addition, although R&D on air oxidation of relevant materials is already under way, some more

attention needs to be paid to the safety of spent fuel pools.

Also it is worthwhile to gain a better understanding of the behaviour of the systems versus the intensity of the applied stress and load, and appreciating how and when it turns to non-linear and/or catastrophic. This may call for an extension of the physical testing and modelling, as well as the development of improved and physically-based computer tools in different fields of endeavour.

In relation with every single area where lessons have been drawn, and on the basis of the stress test reports, the SNETP Task Force finally identified a series of R&D topics with relevant priority, as listed in Table 1. For each of them a deeper discussion will be provided in chapter 4.

Table 1. List of research areas identified for each lesson learned area

LESSON LEARNED AREA	RESEARCH AREAS
Nuclear system organisation, safety infrastructure and safety culture	<ol style="list-style-type: none">1. Systematic assessment of vulnerabilities to defence-in-depth and safety margins for beyond design basis loads2. Human/organisational factors under high stress and harmful conditions
Assessment of risk from external events and prevention measures	<ol style="list-style-type: none">3. Improved methods for external event hazard evaluation4. Use of the probabilistic methods to assess plant safety in relation to extreme events5. Advanced deterministic methods to assess plant safety in relation to extreme events6. Advanced safety systems for nuclear power plants
Phenomenology, management and mitigation of severe accidents	<ol style="list-style-type: none">7. Material behaviour during severe accidents8. Advanced methods for the analysis of severe accidents9. Improved procedures for management of severe accidents10. Assessment of the radiological effects of the severe accidents11. Improved modelling of fuel degradation in the spent fuel pool
Emergency preparedness and management	<ol style="list-style-type: none">12. Methods for minimization of contamination in the NPP surroundings and for treatment of large volume of radioactive waste13. Accident management in the framework of the integrated rescue system

4. Identification of research areas associated with the lessons learned

■ 4.1. Systematic assessment of vulnerabilities to defence-in-depth and safety margins for beyond design basis loads

4.1.1. Lessons learned from the Fukushima accident

The Fukushima accident showed the need for quantification of safety margins (in particular in the case of extreme external hazards) beyond the design basis, up to core damage and major releases of radioactive substances into the environment. This need has been reflected in Europe by the decision to perform the stress tests in all NPPs. There is also a tendency that evaluation should be aimed not only at the external hazards, but generally at all extreme events, i.e. including internal scenarios and man induced ones. The stress tests also showed the need to clarify and harmonise the methodologies, the objectives and the criteria adopted both for design and safety assessment. Moreover, it has been pointed out that the assessment should be based on a comprehensive evaluation of the capacity and reliability of the defence in depth levels, in particular for the third and fourth level of defence, taking into account the need for a quantification of the safety margins beyond the design basis.

4.1.2. Objectives of the activities in this area

The main objective of the activity is the development of the methodology for comprehensive assessment of the defence in depth engineering measures, with special emphasis on those pertaining to the third and fourth level, and the analysis of adequacy of existing methods or development of a new

methodology for a repeated execution of the "stress tests" for both existing and new NPPs with the modelling of the likelihood and extent of damage to components and systems.

4.1.3. Examples of specific tasks in the given area

- Development and validation of methods for comprehensive evaluation of defence in depth measures, in particular for the third and fourth level of defence.
- Determination of the possible effects of extreme events with respect to interrelation between the plant system operation and personnel intervention.
- Development of acknowledged procedures for the assessment of the ultimate resistance of the barriers against releases of radioactive materials to the extreme loads.
- Development of suitable methodology for the identification of threshold phenomena (cliff edges),
- Determination of the sensitivity of the main safety functions, to extreme loads.
- Development of comprehensive models for assessing the behaviour of NPPs under the conditions of the beyond design basis extreme loads.

■ 4.2. Human/organizational factors under high stress and harmful conditions

4.2.1. Lessons learned from the Fukushima accident

The complexity of the decision-making process in managing the accident in Fukushima had a strong impact on the efficiency and timeliness of necessary interventions and was the source of misunderstandings and delays.

It is generally accepted that the need for responses to serious accidents at the same time on several reactors and spent fuel pools exceeded acceptable limits for the workers of Fukushima plant already stressed by the extreme working conditions and long-term impossibility of communication with their families. Some of the operational procedures in place, appropriate for normal operation (top-down decision making) turned to be ineffective for managing accidents. As confirmed by a recent report by the Japanese Government, the human factor has proved to be a critical issue and a weak point in dealing with the accident. Among possible ways to improve accident management, specific training of skilled intervention groups has been identified. The use of more sophisticated instruments for evaluation during the accident could also provide faster guidance for the implementation of possible corrective strategies by the operator.

4.2.2. Objectives of the activities in this area

The analysis of the importance of the human and organisational factors for managing emergencies in the conditions of high stress and harsh working conditions, with the objective of identifying possibilities for improvement and to develop efficient assessment tools and procedures.

4.2.3. Examples of specific tasks in the given area

- Assessment of the importance of human factors in the efficiency of accident management.
- Evaluation of the applicability of standard management methods on the capability of personnel to respond in emergency conditions (influence of routine behaviour on management of extraordinary situations).
- Analysis of the functionality of the various means of communication under conditions of heavily damaged infrastructure.
- Analysis of habitability of working places needed for management of emergencies on the site and beyond.
- Development and updating of training materials for the preparation of emergency response teams, especially for the workers of the technical support centre.
- Evaluation of the effectiveness of interventions under extraordinary conditions (damaged

infrastructure, limited availability of the site, limited human resources).

- Assessment of the needs of redundant technical means and emergency teams for individual units on the given site or a region.
- Assessment of the conditions for the gradual transfer of the responsibility for accident management from the level of operational staff to higher levels of management.
- Assessment of safety culture issues and of their importance for the management of severe accidents,
- Development of methodologies for safety culture oversight.

■ 4.3. Improved methods for external event hazard evaluation

4.3.1. Lessons learned from the Fukushima accident

Hazard evaluation has to be continuously reviewed on the basis of up to date knowledge and expertise. Despite the current trend supporting the use of advanced methods for hazard evaluation, they are still affected by large uncertainties and they are not widely and generally adopted.

4.3.2. Objectives of activities in this area

Development of methodologies for hazard evaluation for low probability events of both natural and man induced (accidental) scenarios. The research will aim at the minimisation of the uncertainties affecting the hazard and to the identification of suitable levels for the design basis values to be used for the design/re-evaluation.

4.3.3. Examples of specific tasks in the given area

- Identification of very rare, extreme internal and external events, potentially leading to common cause failures simultaneously arising on several units at the same site.
- Implementation of suitable methodologies for determining the frequency of occurrence of extreme phenomena with very long period of return,

including the combination of extreme events, even in case of limited availability of historic data.

- Development of methods for hazard evaluation in the case of rare events (i.e. tsunami), with insufficient historic records available.
- Updating of methodologies for site selection in relation to the likelihood of extreme external events.
- Development of methods for expert elicitation⁹ of rare events.

■ 4.4. Use of the probabilistic methods to assess plant safety in relation to extreme events

4.4.1. Lessons learned from the Fukushima accident

Despite the developed level of probability methods and their wide use in design and generally in safety assessments, the Fukushima accident has shown that there are a number of factors, which have not been sufficiently covered in the current PSA studies. It is therefore necessary to further develop more effective modelling tools for wider use of the PSA. Examples of the required improvements include the extension of the reporting period over 24 hours, improved assessment of the impact of the human factors and common cause failures (harmonisation of approaches), consideration of the long-term loss of electric power and heat removal, consideration of potential staff recovery actions and modified configurations and consideration of the occurrence of the accident simultaneously on several units. At the same time, it is necessary to develop integrated assessment methods using both deterministic and probabilistic methods.

Moreover, it could be worth considering a class of probabilistically negligible, but potentially extremely dangerous events that could engender detrimental consequences. That could be done, e.g., adopting specific approaches to address the residual-risk management instead of relying upon the conventional PSA which could drive to misleading conclusions, due to low probability.

4.4.2. Objectives of the activities in this area

Improvement of the methodologies, harmonisation of the criteria and extended range of

applicability of the methods with emphasis on a more comprehensive consideration of extreme external hazards, their combinations and the consequences of these hazards with prolonged duration and simultaneous occurrence on several units.

4.4.3. Examples of specific tasks in the given area

- Probabilistic approach for external events (flooding, climatic events), use of screening methods, assessment on the maturity and applicability of existing methods, or development of new ones.
- Assessment of restrictions in the use of the results of the PSA.
- Rules for practical elimination of mechanisms, leading to large damage to fuel and to large release of radioactive materials.
- Methods for the evaluation of component failure modes in relation to extreme, low probability scenarios, in case of lack of experimental data, by analysis and similarity.
- Development of probabilistic models aimed at the analysis of the reliability of human factors, analysis of common cause failures, behaviour of the spent fuel pool, consideration of prolonged loss of the ultimate heat sink, long term loss of electrical supply, availability off-site for the external help.
- Quantification within PSA: extended periods of the accident (more than 24 hours), interactions between the interventions of the operators and the automatic operation of systems, the consequences of the presence of several units on the same site and the sharing of equipment and personnel (common equipment, the links between the units, the availability of operating personnel), evaluation of the reliability of recovery actions under harsh conditions, the consideration of corrective actions in the case of extreme external hazards.
- Consideration of the status and availability of reliable information on the infrastructure actual status in the PSA studies.
- Assessment of the reliability of innovative design solutions, in particular the passive systems.
- Methodology for probabilistic assessment of security threats to NPPs.
- Assessment of the PSA predictions vs. the reliability of the safety and safeguard systems and the efficiency of the detection, repair and replacement of components.

9 - Expert elicitation is an established term: In science, engineering, and research, expert elicitation is the synthesis of opinions of experts of a subject where there is uncertainty due to insufficient data or when such data is unattainable because of physical constraints or lack of resources. Expert elicitation is essentially a scientific consensus methodology. It is often used in the study of rare events. Expert elicitation allows for parameterization, an "educated guess", for the respective topic under study. Expert elicitation generally quantifies uncertainty.

- Expert elicitation tends to be multidisciplinary as well as interdisciplinary, with practically universal applicability, and is used in a broad range of fields. Prominent recent expert elicitation applications are to climate change, modelling seismic hazard and damage, association of tornado damage to wind speed in developing the Enhanced Fujita Scale, and risk analysis for nuclear waste storage.

- consideration of possible conflicting interactions between different safety systems (or functions),
- development of specific approaches derived from other fields of endeavour (finance, assurance) to address the residual-risk management .

■ 4.5. Advanced deterministic methods to assess plant safety in relation to extreme events

4.5.1. Lessons learned from the Fukushima accident

Quantification of the safety margins (in particular in the case of extreme external hazards) in the stress tests initiated by the Fukushima accident, in addition to drawing up systematic procedures of evaluation of defence in depth protection also requires sufficiently detailed methods of evaluation of the level of damage to structures, systems and components under beyond design basis loads. The evaluation of such scope of damage was not a normal part of the safety analysis within the licensing of the plants and in many cases in the stress tests it was therefore necessary to use simplified engineering estimates. In connection with a new interpretation of the safety margins (above the licensing limits) for the anticipated future analyses it is necessary to develop, harmonise and apply the methods of assessment of damage to equipment.

4.5.2. Objectives of the activities in this area

Improvement and harmonisation of methods for the assessment of the extent of the damage to structures, components and systems of NPP under various extreme loads beyond the design basis, their combinations and measures for the elimination or mitigation of the damage.

4.5.3. Examples of specific tasks in the given area

- Analysis of operating experience from the events initiated by unpredicted external events.
- Updating of methods for the assessment of the consequences of hazards caused both by geophysical factors and extreme weather conditions.

- Methodology for determination of the secondary effects of earthquakes, including the loss of the ultimate heat sink, floods, fires, loss of coolant, destruction of infrastructure, disruption of the access of personnel to the site, the dynamic effects of the destruction of the civil structures, hydrogen explosions.
- Modelling the effects of individual beyond design basis extreme events and their combinations on the damage of structures, components and systems, the identification and potential for avoidance of threshold phenomena (cliff edges),
- Reassessment of the criteria for the design and evaluation of the effectiveness of protection against external hazards.
- Analysis of the operability of safety important equipment at the beyond design basis extreme events.
- Analysis of extreme events initiated by potential terrorist attacks, including those induced by external missiles, fires, blasts and explosions and specific issues with cyber attack, hacking and system vulnerability (through the definition of a comprehensive envelope load that the plant should be able to resist)¹⁰.

■ 4.6. Advanced safety systems for nuclear power plants

4.6.1. Lessons learned from the Fukushima accident

The main cause of the destruction of the Fukushima plant was a long-term interruption of electric power and consequently the loss of possibility of cooling the core and the containment by active systems. It is acknowledged that a more extensive use of passive systems, i.e. systems able to perform their function without external energy supply, could have contributed to prevent the catastrophic consequences from such an accident. Nevertheless, it is to be remembered that the isolation condenser (a passive safety system) in Fukushima did not prevent the core from melting. Suggestion could also be made to extend the investigation to the self-operated systems which could show-up both more effective and practical than the equivalent passive ones. Moreover they could provide a wider diversity.

In some new reactor designs, passive systems are more extensively adopted. Nevertheless, their use is not fully care-less. Examples of potential

10 - Even though this topic cannot be considered as a direct consequence of the Fukushima's events, nevertheless it was broadly discussed during the stress-test. Actually, its extreme sensitivity and confidentiality, can limit the space for international collaboration. Nevertheless, it is worth to be mentioned because it contributes significantly to the definitions of the loads the nuclear installation is intended to resist, independently of their nature and origin.



problems include the quantification of system reliability, the application of the single failure criterion, the so-called phenomenological failures. Questions arise in particular for systems using small driving forces, based on the natural circulation. For convincing confirmation of reliable functioning of these systems, further theoretical and experimental research is needed.

4.6.2. Objectives of the activities in this area

Acquisition of the necessary knowledge and methods, demonstration of the reliability and functional capabilities of the innovative safety systems and components, in particular systems based on passive features.

4.6.3. Examples of specific tasks in the given area

Modelling the behaviour and assessing the efficiency and reliability of passive equipment and components, e.g.

- Improved battery autonomy.
- Pre-pressurized core flooding tanks (accumulators).
- Elevated tank, natural circulation loops (core make-up tanks).
- Gravity drain tanks,
- Passive coolers for secondary side of steam generators based on natural circulation.
- Passive cooling circuits for containment heat removal.
- Passively cooled core isolation condensers.
- Passive filtered containment venting systems.
- Pump natural circulation.
- Passive hydrogen recombiners.

■ 4.7. Advanced materials for nuclear power

4.7.1. Lessons learned from the Fukushima accident

A significant way to mitigate the consequences of the multiple accidents, as in the case in Fukushima, would be the adoption of innovative materials, able to better withstand the

loads and more resistant to severe accident conditions, with smaller production of hydrogen and lower staff radiation doses, etc. An example of a more long-term activity is to replace zirconium based claddings by silicon-carbide based ones to eliminate hydrogen production. To assess the safety margins of key components (fuel, fuel claddings, reactor vessel and containment) for present and future reactors, it is needed to know the material properties in end-of-life conditions and during transients arising from accidents. It is also important to determine the variation of properties for inclusion in probabilistic assessments.

4.7.2. Objectives of the activities in this area

Development of new structural materials for nuclear components with increased resistance to harsh operating conditions (corrosion, high radiation doses, high-frequency thermal and mechanical fatigue) and improvement of knowledge existing and also new ones, through testing and modelling. International co-operation is needed for the development of new materials for current (e.g. cladding materials) but especially for new reactors.

4.7.3. Examples of specific tasks in the given area

- Further assessment of existing fuel and cladding materials in conditions of severe accidents and development of new fuel and cladding materials with increased resistance and improved coolability during severe accidents.
- Assessment of existing and development of new structural materials for spent fuel storage (including dry storage) aimed at increasing their resistance to hazards.
- Further assessing the degradation mechanism and ageing of materials.
- Developing simulation and monitoring of degradation, including non-metallic materials, cables and civil structures.
- Modelling and testing of the behaviour of components under severe accident conditions.
- Conduction of test programmes to determine material properties under severe accident conditions (e.g. irradiation, strain rate, high temperature) and development of data base to support analysis.

- Evaluation of how the use of non-standard cooling media (e.g. polluted water) affect the integrity and functioning of components (e.g. blocking of valves, dampers, creation of deposits on cladding, effects on material of the reactor vessel, etc).

■ 4.8. Advanced methods for the analysis of severe accidents

4.8.1. Lessons learned from the Fukushima accident

The accident has shown that despite preventive measures, some accidental sequences (though for very unlikely conditions) may develop into a severe accident. They can eventually lead to melting the core, damaging the safety barriers and resulting in the dispersion of radioactive materials from the containment, with consequential risk to the surroundings of the plant. While the Fukushima accident did not reveal any fundamentally new, unknown phenomena, it did show that the ability to predict the course and consequences of the accident and the results of the analyses are limited because of large uncertainties, especially in the case of modelling of long-term processes. Although the analysis already undertaken has helped significantly in the interpretation of the course of the accident, there are still gaps in knowledge of the sources and the distribution of hydrogen, the quantitative scale of the core melting and the mechanism of relocation of the core to the containment, about absorption of fission products in the pressure suppression tank and the behaviour of iodine and other areas.

4.8.2. Objectives of the activities in this area

Critical assessment of the state of the art, improvement and validation of robust computational tools for the comprehensive evaluation of the course of accidents in the reactor cooling system and in the containment, from the initiation up to its transition to the severe accident phase, with a view of reducing the uncertainty in the results. Fulfilment of that objective will also require experimental research and must be implemented by a broad international co-operation at least within the EU.

4.8.3. Examples of specific tasks in the given area¹¹

- Critical assessment of the status of knowledge (state of the art) in the modelling of severe accidents.
- Development and validation of models and simulation platforms for the analysis of severe accidents with emphasis on phenomena that are currently regarded as insufficiently understood.
- Evaluation and validation of the computer codes and assessment of the uncertainties associated with severe accidents.
- Modelling of core heating, chemical reactions, degradation of the core, post-accident heat removal, coolability of overheated and partially destroyed core.
- Detailed examination of the interaction of materials under conditions of severe accidents, including the interaction of molten corium with concrete.
- Detailed examination of the possibilities of stabilisation of molten corium in the reactor vessel or in the containment.
- Detailed examination of efficiency of filtered containment venting.
- Analysis of the spectrum of scenarios in progression of core melting in the reactor vessel or corium in the containment (not only the final stage).
- Production, distribution and accumulation of hydrogen, the mechanisms of flame acceleration and the transition from deflagration to detonation.
- Issues of recriticality in complex geometries caused by severe damage of the core, coolant injection and boron dilution.

■ 4.9. Improved procedures for management of severe accidents

4.9.1. Lessons learned from the Fukushima accident

The development and the consequences of the Fukushima accident have demonstrated that despite the large volume of existing knowledge and the efforts of the staff it was not possible either to prevent the accident or to mitigate it without endangering the environment. Although the actual cause of the failure to manage the accident is not entirely clear, the



underestimation of the combined effect of the earthquake and the tsunami wave led to the sequential disabling of safety barriers at several levels, with the loss of the integrity of the fuel cladding, the fuel matrix, the reactor cooling system, and to some extent also of the containment, with the subsequent dissemination of radioactive substances into the surroundings. For a long time it was impossible to restore electrical power supply to important systems and also to recover heat removal from nuclear fuel from the containment. The staff failed to prevent the hydrogen explosions, which caused great damage to 4 units. A particular problem was the need to deal with the accident in the absence of information from the instrumentation, while having simultaneous occurrence of accidents at several units on the site, with limited number of staff, and extensive destruction of infrastructure.

4.9.2. Objectives of the activities in this area

Update of the basic knowledge about the causes and consequences of severe accidents, and development of simple computational aids and alternative ways of obtaining information regarding the status and expected development of the accident, with the possibility to verify the effectiveness and extension of the scope of severe accident management strategies, determination of the rules for the timely deployment and prioritisation of strategies.

4.9.3. Examples of specific tasks in the given area

- Update of possible accident management strategies, taking into account their positive and negative effects.
- Optimisation and validation of strategies and guidelines for accident management, including simple but robust and effective passive measures.
- Investigation of new options for improved strategies for accident management and their prioritisation.
- Improving the functional ability of instrumentation in conditions of severe accidents, increasing the reliability of the information from the instrumentation relevant to the management of accidents, development of alternative ways of obtaining information in cases where the loss of DC

power supply prevents the reading of standard instruments.

- development of robust tools and computing devices (prediction models) needed for management of accidents, including on line ICT tools operating in real time to aid decision making process.
- use of advanced simulators to improve operators preparedness to avoid cliff edge effects.
- analysis of the possibilities for prevention of containment bypass.
- analysis of the possibilities of containment overpressurization, assessment of positive and negative impacts of containment venting.
- accurate monitoring and classifying all possible on-site and off-site intervention means.

■ 4.10. Assessment of the radiological effects of the severe accidents

4.10.1. Lessons learned from the Fukushima accident

Nuclear safety is primarily associated with the ability to prevent releases of radioactive materials, which could endanger the surroundings of the plant. In this connection Fukushima showed a number of weaknesses. Data presented on the radiological consequences consider only a few isotopes of iodine and caesium, while in the case of a severe accident a substantially wider range of radioisotopes is expected. In the modelling it would be appropriate to refine the description of the links between weather conditions during an accident at a NPP (ventilation into the surroundings, the explosions and fires, measures for detention and fixation of radionuclides) and radiological consequences. A useful tool would be a more accurate determination of the relation between the scale of the damage, composition of the source term and measured dose rates.

The issue of radiological consequences of reactor accidents deserves more attention regardless of Fukushima.

4.10.2. Objectives of the activities in this area

Improvement of both probabilistic and deterministic computational tools and enhanced

modelling of radiological consequences of reactor accidents, with higher flexibility in considering links to the processes and activities in the plant. In addition more accurate description of the conditions for the transport of radioactive materials in the vicinity of the plant should be required and the development of proposals on the possibility of reduction of the radiological source term to the environment.

4.10.3. Examples of specific tasks in the given area

- Determination of the release of individual radioisotopes from heavily damaged fuel, their physical and chemical forms.
- Improved modelling of chemical and physical forms of released radioactive materials from heavily damaged fuel.
- Improvement and validation of models for dissemination of radioactive materials in the atmosphere and in aquatic systems, including possible effects of explosions and fires in the vicinity of sources of radioactive materials.
- Development of probabilistic methods for contamination simulation (PSA level 3).
- The use of high-quality meteorological data and weather forecasts in the analysis of radiological consequences.
- Harmonisation of the methods of transfer of data suitable for prediction of radiological consequences,
- Prediction of the effects of radioactive releases to the environment.
- Assessment of the current state of knowledge in the field of the health effects of low doses of radiation.

■ 4.11. Improved modelling of fuel degradation in the spent fuel pool

4.11.1. Lessons learned from the Fukushima accident

Although the latest observations have shown relatively limited damage to the fuel and spent fuel pool itself in the 4th unit of Fukushima Dai-ichi, interim evaluation drew attention to the potential severity of the accident in the spent fuel pool as a significant source of radioactive materials. There are several impor-

tant differences between accidents (including severe accidents) taking place in the reactors and in the SFPs. For example, the long duration of the processes in the SFP has an effect on the quantitative release fractions of various radioisotopes. In addition, all processes of cladding oxidation, fuel relocation and release of fission products take place in high temperature air atmosphere instead of in steam.

Despite the large thermal inertia of the pool in Fukushima, there were several negative factors for the management of the accident, including the location of the pool in the upper part of the building, which made it less accessible for replenishment of the coolant inventory, and outside the containment. Although, in this case it was the explosion of hydrogen, which caused the destruction of the reactor building, probably due to penetration from the adjacent Unit. 3, in a similar manner this could have occurred after the uncovering and overheating of the fuel in the pool. Another way of fuel overheating could be the loss of coolant from in the pool as a result of cracks caused by the earthquake. Under unfavourable circumstances the pool could become a source of release of radioactive materials, the effect of which would be further boosted by explosion of hydrogen and fire in the building. Doubts about the status of the pool forced the operating personnel in the long-term to refill the pool by different means (helicopters, fire trucks).

4.11.2. Objectives of the activities in this area

Improvement of the status of knowledge, development and verification of adequate computational means for the assessment of processes with failure of heat removal from the spent fuel pools (possibly also from dry storage of spent fuel) including transition into a severe accident with fuel melting, and systematic reassessment of all the possibilities of occurrence and development of accidents in spent fuel pools.

4.11.3. Examples of specific tasks in the given area¹²

- Re-assessment of accidents in spent fuel pools caused by loss of cooling and boiling of the coolant.



- Identification of potential pathways leading to severe accidents with fuel melting.
- Mechanisms of fuel degradation in the spent fuel pool, focusing on late phase phenomena and 3D effects.
- Creation of chemical forms of the substances produced in heavily damaged fuel in the pool, taking into account the presence of an highly oxidizing atmosphere.
- Evaluation of the possibility of the re-criticality in the spent fuel pool (including situations without fuel damage).
- Possibility of production of hydrogen and the consequences of deflagration and detonation of hydrogen.
- Specific conditions for the source term and for dissemination of radioactive materials.
- Measures for the prevention of the degradation of nuclear fuel.
- Measures for mitigating the consequences of cases where prevention failed.
- Methodology of analysis of the integrity of barriers in relation to the spent fuel pool.

■ 4.12. Methods for minimization of contamination in the NPP surroundings and for treatment of large volume of radioactive waste

4.12.1. Lessons learned from the Fukushima accident

Assessment of the radiological conditions in a wide area around the NPP and mitigation of the effects of contamination on the population and the environment have been key challenges not only since the beginning of the accident to the present day, but such tasks remain relevant for the next few years. The ultimate goal is the complete renovation and restoration of contaminated territory. It was also shown that attention should be paid to the various possibilities for reducing the dose rates on the site and in the surrounding as well as to the isolation and fixation of the radioactive materials released outside the NPP.

4.12.2. Objectives of the activities in this area

Evaluation of the effectiveness of existing methods of radiological environmental monitoring as well as the effectiveness and availability of the technical means for the rehabilitation of potentially contaminated territory.

4.12.3. Examples of specific tasks in the given area

- Evaluation of the potential extent of the contamination of the environment and its impact in the case of a radiation accident.
- Methods of identification and assessment of the effects of the released radioactive materials.
- Methods of fixation of radioactive substances on the contaminated territory.
- Evaluation of methods and means of radiological environmental monitoring, assessment of the resistance of the off-site monitoring network against extreme external hazards.
- Availability and efficiency of technical means for the elimination of the consequences of accidents and the rehabilitation of the territory.

■ 4.13. Accident management in the framework of the integrated rescue system

4.13.1. Lessons learned from the Fukushima accident

A separate problem in Fukushima was the implementation of measures to protect the population up to a distance of a few tens of kilometres from the plant, including the information to the public, implementation of the rescue and evacuation plans and coordination of decision-making on all relevant levels of management.

A significant weakness in the course of the accident was the way of communicating the radiological data to the public. Various measurement units were used; presented data did not permit their easy interpretation from the perspective of the seriousness of the threat; different technical values were alternately presented (doses, dose rates); a link between the

12 - The topics addressed in this section are intended to span a wide field of R&D issues, which are intended to be effectively eliminated in current designs, such as the fuel degradation mechanism and the recriticality under degraded conditions in the spent fuel pools. Despite the post-accident investigations in Fukushima, eventually reducing the importance of such phenomena, these phenomena are considered as relevant for R&D activities,

presented data and possible health effects was not clear. The shortcomings of the INES scale as a tool of communication with the public was also demonstrated, assigning to the Fukushima accident the same degree of severity as to the Chernobyl accident, at a significantly different level of risk.

Evacuation of the population within a radius of 30 km around the power plant was needed, which concerned approximately 185,000 people. The decision on how to deal with the accident was not made in a sufficiently short time for the chosen method to be effective. It was not entirely clear how to determine evacuation zones depending on the anticipated doses, therefore their reassessment is planned.

4.13.2. Objectives of the activities in this area

Evaluation of the current status and proposal for improvements of the integrated rescue systems at the national level, with emphasis on the management of accidents of NPPs.

4.13.3. Examples of specific tasks in the given area

- Evaluation of the effectiveness of the current rescue system for management of accidents at NPPs in view of the experience of the Fukushima plant, including the assessment of its applicability for other hazards (e.g. chemical accidents), using international experience.
- Improvement of the methods of risk assessment in the neighbourhood depending on the size and other characteristics of the source term for various types of hazardous substances.
- assessment of needs and feasibility of external support to the NPP at corporate, national and international level.
- Detailed development of methodology documents and instructions for radiation protection in radiation emergencies.
- Identification of the necessary technical resources and the development of training programmes for intervention teams.
- Detailed development of training programmes for emergency drills at the national level.
- Detailed development of scenarios for emergency drills, including evaluation criteria for success,
- Assessment of the size of evacuation zones in case of natural disasters.
- Evaluation and proposal for improvements of the system for informing the public, the communication of risk to the public, including the coordination of the preparation and implementation of the evacuation of the population.
- Review of the suitability of the INES scale as a tool of communication with the public regarding the severity of the accident.
- The harmonisation of criteria of acceptability and intervention levels for radiation accidents.
- Proposal for technical and organisational measures for the improvement of integrated rescue systems.

5. Basic insights related to research needs for Gen II and III reactors

■ 5.1 Overview

The NUGENIA association has defined eight topic areas to identify future R&D needs, as listed below:

1. Plant Safety and Risk Assessment.
2. Severe Accidents.
3. Core and Reactor Operation.
4. Integrity Assessment and Ageing of System Structures and Components.
5. Fuel Development, Waste and Spent Fuel Management and Decommissioning.
6. Innovative Gen III Design.
7. Harmonisation.
8. Inspection and Qualification.
1. Systematic assessment of vulnerabilities to defence-in-depth and safety margins for beyond design basis loads.
2. Human/organisational factors under high stress and harmful conditions.
3. Improved methods for external event hazard evaluation.
4. Use of the probabilistic methods to assess plant safety in relation to extreme events.
5. Advanced deterministic methods to assess plant safety in relation to extreme events.
6. Advanced safety systems for nuclear power plants.
7. Material behaviour during severe accident.
8. Advanced methods for the analysis of severe accidents.
9. Improved procedures for management of severe accidents.
10. Assessment of the radiological effects of the severe accidents.
11. Improved modelling of fuel degradation in the spent fuel pool.
12. Methods for minimisation of contamination in the NPP surroundings and for treatment of large volume of radioactive waste.
13. Accident management in the framework of the integrated rescue system.

This section of the report therefore the basic insights for the research needs identified by the Task Group and wonders how they may impact on the scope defined by the road maps for each of these topic areas. It also takes into account the research topics identified in section 3.7 above.

It has been generally concluded to date, that the Fukushima incident has not led to the requirement for any new key R&D target areas, but rather an enhancement of the existing ones to accommodate any additional considerations. The implications of the incident might also lead to a different emphasis on the scope of particular R&D areas. This remains true for the eight NUGENIA topic areas and those identified in section 3.7.

■ 5.2 Research areas

In adopting a complementary approach to that employed to identify the NUGENIA R&D target areas, the Task Group defined thirteen research areas following a review of the Dai-ichi accident, as defined in chapter 4 of this report. To recap, these are:

Not surprisingly there has been a tendency to focus on severe external hazards and their implications, but other areas must not be neglected as well. In the following section an attempt is made to map the implications arising from the above thirteen areas onto the eight NUGENIA Technical Areas. In most cases this leads only to the identification of additional aspects or potentially a change of emphasis on the existing ones.

A mapping of interaction between the research areas identified in this report and the NUGENIA Technical Areas is provided in table 2 below.

Table 2 – Correlation among the proposed research areas and the NUGENIA Technical Areas

PROPOSED RESEARCH AREAS	NUGENIA TECHNICAL AREAS							
	1 - Plant safety & risk assessment	2 - Severe accidents	3 - Core & reactor operation	4 - Integrity assessment & ageing of system structures & components	5 - Fuel development, waste & spent fuel management & decommissioning	6 - Innovative Gen-III design	7 - Harmonisation	8 - Inspection & qualification
1 - Systematic assessment of vulnerabilities to defence-in-depth and safety margins for beyond design basis loads	++	+		+			+	
2 - Human/organisational factors under high stress and harmful conditions	+	+	++				+	
3 - Improved methods for external event hazard evaluation	++	+	+				+	
4 - Use of the probabilistic methods to assess plant safety in relation to extreme events	++	+		+			+	
5 - Advanced deterministic methods to assess plant safety in relation to extreme events	++	+				+	+	
6 - Advanced safety systems for nuclear power plants	++	+	+			+	+	+
7 - Material behaviour during severe accidents	+	+		++	+	+	+	+
8 - Advanced methods for the analysis of severe accidents	+	++						
9 - Improved procedures for management of severe accidents	+	++	+				+	+
10 - Assessment of the radiological effects of the severe accidents	+	++	+				+	
11 - Improved modelling of fuel degradation in the spent fuel pool	+	+	+		++			
12 - Methods for minimisation of contamination in the NPP surroundings and for treatment of large volume of radioactive waste		+			+			
13 - Accident management in the framework of the integrated rescue system	+	+	+				+	+

The number of + indicates the level of correlation of each NUGENIA's Topic Area in the field of endeavour, as defined in the roadmaps. It also allows viewing the sharing of different topics among NUGENIA's Topical Area



■ 5.3 Implications for NUGENIA Technical Areas

Table 2 summarises the correlation among the proposed research areas and the NUGENIA's Topics. To facilitate the understanding, the following chapter recalls the current topics roadmap content. Each NUGENIA topic area has been sub-divided into individual research fields. The relevance and implications for scope and prioritisation of the research needs for each topic area is discussed. The ETSON position paper [10] produced by ETSON has provided valuable input to this exercise. As the paper rightly points out however, it should be noted that the priorities for research subjects may be different to those identified by system designers and utilities. As the NUGENIA road maps have not yet been fully developed or endorsed by the utilities this must be recognised.

5.3.1 Plant Safety and Risk

The road map for this topic area has been divided into seven fields:

1. Data, methods and tools for risk assessments.
2. Plant transients.
3. External loads (environmental impact on NPPs) and hazards.
4. Electrical disturbances from the grid to the plant.
5. Human performance and safety culture.
6. Advanced safety assessment methodologies.
7. Design of reactor safety system.

This is a comprehensive set of research fields and encompasses many of the areas highlighted in [10]. It is however important that field 5 includes the aspects associated with human performance under situations of extreme stress, which has been highlighted following the Fukushima incident.

5.3.2 Severe Accidents

The priority topics identified for this target area under SARNET were: in-vessel core coolability, molten core-concrete interaction, fuel-coolant interaction, hydrogen mixing and combustion in containment, impact of oxidising

conditions on source term, and iodine and ruthenium chemistry. It can be deduced from this list that the R&D identified for severe accidents encompasses the issues arising from the Fukushima incident. The only addition to scope should be the implications of prolonged station black out.

The road map for this area has been split into 6 fields:

1. Corium/debris coolability (in-vessel, ex-vessel).
2. Molten core-concrete interaction.
3. Steam explosion and hydrogen combustion in containment.
4. Source term (as released from the NPP to the environment).
5. Modelling of severe accident scenarios (integral codes, PSA level 2 and 3, emergency situations).
6. Impact of severe accidents on the environment (near field out of the NPP).

These research fields cover the main issues identified in [10] and chapter 4 of this report.

5.3.3 Core and reactor operation

The road map for this area has been split into 5 fields:

1. Human and organizational factors.
2. Integration of digital technologies.
3. Numerical modelling and core optimization.
4. Water chemistry and LLW management.
5. Radioprotection.

These align closely with a number of areas identified in [10] and chapter 4; consequently no new R & D needs are identified.

5.3.4 Integrity assessment of systems, structures and components

This topic area has been divided into five fields:

1. Integrity assessment.
2. Materials performance.
3. Ageing.
4. Functionality.
5. Qualification of methods, equipment and materials.

These fields cover all of the areas identified in chapter 4, but their scope must be extended to include performance under more extreme conditions that originally envisaged

One of the major items was R&D work to seek for optimisation of materials performance/selection. It is recognised that nuclear grade material assessment is a long duration process that requires an early start. The four critical areas for material selection are considered to be:

- **Fuel cladding.**
- **Reactor pressure vessel.**
- **Primary circuit components and pipe-work.**
- **Concrete containment structures.**

The reactor vessel is a key component for safety and requires continuous R&D. The primary containment barrier has to be maintained for all loadings and over the entire lifetime. Major life limiters are the degradation mechanisms that cause embrittlement, and it is important to continue to address them in the near term and especially as the design life is extended. In the aftermath of the Fukushima accident there will be even stricter requirements to demonstrate the integrity of the reactor vessel and fuel cladding under severe accident scenarios. With regard to the third point, existing materials and coatings that are not yet used in the nuclear environment were considered to have potential benefits. It will be necessary to ensure that the duties specified for such new materials take into account a suitably extended parameter range. Component manufacturing methods and assembly technology were identified as topics and the latter in particular must not lead to reduction of the robustness of construction. In particular the response to seismic, other dynamic environmental loadings and blast damage must be considered. This must not only cover the common components but also cables, electronics and support structures.

Reinforced concrete containment structures provide the third barrier to radioactive releases and there have been significant improvements in the development of materials that can withstand high temperatures whilst maintaining high strength. This is particularly relevant as the decision to depressurise the Dai-ichi containment was a consequence of the design pressure being exceeded due to the combination of hydrogen, steam and normal inert gas filling.

With regard to ageing, industrial obsolescence

was an important factor in the Dai-ichi plant response to the tsunami. Thus in considering this topic the important consequences for future designs must be recognised. Comparatively speaking the nuclear industry is a small player with the market being driven by other industries. Products become obsolete in a timescale which is short in comparison to the potential 60 – 80 year life projected for future reactors. In addition if more “off the shelf” items are used technologies and components may become harder to replace and may not be so easy to fulfil nuclear requirements. This R&D topic must therefore encompass this possibility and must investigate the development of obsolescent resistant technologies. The vulnerability of such digital and wireless devices must be assessed against more challenging environments than those considered to date.

5.3.5 Fuel development, waste and spent fuel management and decommissioning

The road map for this topic area has been divided into five fields:

1. **Fuel development for existing, advanced and innovative core designs.**
2. **Fuel behaviour mechanisms and computational codes.**
3. **Fuel transportation, interim storage and treatment.**
4. **Waste and spent fuel management.**
5. **Decommissioning/dismantling.**

This NUGENIA topic area potentially covers an extremely wide range of research areas. Fuel design, behaviour, transportation and interim storage are all areas that have been identified as being extremely important following the Fukushima incident. As there is some potential overlap with topic area 3, care must be taken that no significant areas are missed by either topic area road map.

The condition of the fuel is a major consideration in the evolution of any NPP accident scenario as it is the major contributor to the ultimate severity of the consequences.

The original R&D topics identified for fuel focussed on four main areas:

- **Improved understanding of fuel assembly behaviour.**



- **Development and extension of two phase flow CFD computational capacity and coupling methods.**
- **Advanced fuel design to increase integrity and reliability while achieving high performance.**
- **Innovative fuel designs with higher enrichment.**

By simple extension, these four areas still encompass the issues that have arisen due to Fukushima.

Improved understanding of fuel assembly behaviour includes improved understanding of fuel resistance in environmental conditions, predictive modelling of fission product release and development of advanced numerical simulation capabilities for modelling material microstructure evolution in relation to corrosion and hydrogen embrittlement. Pellet-clad mechanical interaction and stress corrosion cracking are also included in this area. All of these topics are relevant; it is only the range of investigation that may need to be extended to cover more extreme environmental conditions.

Development and extension of two phase flow CFD may need to consider potentially even more complex geometries than those originally envisaged, to accommodate partially damaged cores during accident evolution. The configuration and condition of fuel in dried out cooling ponds should also be considered in the range of such calculations.

Advanced fuel design will not only have to consider increases in integrity and reliability during normal operation, but also more robustness to accommodate harsher environmental conditions. One of the major concerns is rapid oxidation of the cladding when exposed to high temperature in a steam environment, leading to brittle failure. In this context the focus may be on alternative advanced cladding materials such as ceramics or carbon based composites. Another option to be considered could be the use of coatings.

Interaction of fuel cladding with alternative coolants, such as sea water that could arise during accident scenarios may be another area that should be considered for study.

The topic of innovative fuel design with higher (>5%) enrichment also encompasses the previous item, as it may require advanced materials and cladding integrity. It will also need to consider the implications of fission product retention at high burn up and the potential impact on spent fuel storage.

An additional overarching requirement was improvement and advances in instrumentation and diagnostics to acquire data for the above areas. This requirement for advanced, reliable and robust instrumentation for assessment of reactor performance is consistent with needs identified from the Fukushima investigations.

Fuel behaviour and in particular clad ballooning and fuel relocation during operation have also been highlighted as focus areas.

The Fukushima incident highlighted the dependence on forced water circulation for cooling of spent fuel in interim water pools. It is clear that improvements in the design and modelling of spent fuel ponds and passive heat removal systems will become increasingly important.

Acceptable and safe solutions for radioactive waste produced during the various stages of the nuclear fuel cycle was identified as one of the 8 key R&D target areas at the SNETP Governing Board of 31 March 2011. Management of nuclear waste needs further significant research efforts.

Operation of nuclear reactors generates radioactivity that has to be managed to achieve an optimised approach to minimize worker dose, public exposure and radioactive waste. As a result five main topics can be identified:

- **Control of mobilisation, transport and deposition of source material within primary circuit.**
- **Use of simple remediation technologies to clean/decontaminate primary circuits and/or fuel.**
- **Application of major remedial technologies to replace large components and permit life extension.**
- **Treatment of radioactive waste to reduce volume, improve its stability and recover materials for reuse.**
- **Minimisation of source term in case of a severe accident.**

In considering this target area in relation to the basic insights arising as a consequence of the Fukushima incident, minimisation of the source term is obviously a key item in relation to radioactivity release. Transport and deposition of source material within the primary circuit and its possible subsequent release needs to be considered both during normal operation and accident scenarios. The design of circuits and components was already identified as an item that should address the potential for reduction

of erosion/corrosion, which in turn leads to more robust plants able to accommodate more onerous fault conditions. This should be extended to include overall plant layout, proximity of safety critical potentially vulnerable systems and issues associated with shared services on multiple reactor sites. This should also feed into design manuals and guidelines using lessons learned from experience and good practice.

Development of improved remediation technologies both for decontamination and replacement of large components are areas that are directly relevant. If plant life extension is to be considered, the design criteria for such replacements should take into account revised operational limits to accommodate more onerous duty and resistance to external hazards.

Improved methods for dealing with radioactive waste, both in terms of volume reduction and treatment methods is an area that already had a high profile in terms of public acceptance of nuclear power generation. The Fukushima events have resulted in increased scrutiny of the manner in which large volumes of both liquid and solid waste should be dealt with.

The implications of long term storage of waste and potentially dry storage of fuel at NPP need to be reviewed in the light of Fukushima particularly in relation to the ageing characteristics of such stores and their ability to withstand external hazards.

In the light of Fukushima, research into decommissioning, dismantling and decontamination methods should be extended to consider the additional difficulties and techniques required to deal with potentially damaged nuclear facilities.

5.3.6 Innovative Gen III Design

The road map for this topic area is divided into 5 fields:

1. Innovative technologies for reactor components design and construction.
2. Innovative LWR concepts such as: High Conversion Ratio LWR/Small Modular Reactor.
3. Innovative Gen III specific operation and safety approach.
4. Key success factors for innovative Gen III deployment.
5. Public acceptance drivers for new builds.

This research area is somewhat different to the others as it incorporates some elements that are also covered in other topic area road maps. The task is focussed on Gen III reactors encompassing both pressurised water and boiling water cooled technologies. Consequently its primary aim is to consider the R&D needs for optimisation of reactor construction costs and time as well as the ratio of reactor performance to safety and reliability for long term operation of 60 to 80 years.

Within this context the implications of having multiple reactor units on one site with shared services will need to be reconsidered.

Fields 4 & 5 will take on additional emphasis as a consequence of the Fukushima incident.

No additional aspects are required for this target area as they are covered in the other sections.

5.3.7 Harmonisation

The Harmonisation topic area roadmap in NUGENIA identified four fields of research:

1. Pre-normative research.
 2. Plant design, construction and operation methodologies and practices.
 3. Harmonisation of safety objectives and practices.
 4. Harmonisation of standards.
- The pre-normative research, is defined as both the preliminary phase of research aimed at better characterising new technologies and evaluating the related safety aspects by applying well established procedures and methodologies and a study of the results which are to be used to develop regulations, standards and technical codes.

As an outcome of the Fukushima events, the following topics can be targeted, among others, for pre-normative research activities:

- Structures and components (metallic, concrete), aiming at characterizing their capabilities and limits following standardized definitions, also accounting for the ageing management which needs anticipated assessment of long term phenomena related to corrosion, thermo-mechanics, irradiation, fluid–structure interaction.
- Instrumentation, to increase its robustness and reliability, in extreme high temperatures and high pressure conditions.



- High performance computing, to enhance the capacity to carry out numerous calculations in a very short time, for uncertainty and sensitivity evaluation.
- The plant design, construction and operation methodologies and practices.

The current trend to accounting for whatever is unknown and uncertain in nuclear safety is adopting the defence-in-depth approach, which allows accounting for the uncertainties - which are known - relying on study rules of the deterministic demonstration and of probabilistic approach, as well.

Fukushima events confirmed that the main weakness in the defence in depth is to be searched for in the independence of the defence levels from each other: each device (system, structure, component, operation procedure, etc.) belonging to one level of defence is to be as independent as reasonably possible from any other. Improvements are to be searched for, mainly to put the current GEN II reactor requirements in conformity with those adopted for GEN III and GEN III+.

To complement the current approach, the following should be improved and extended:

- The safety margins approach - which is intended to account for all major potential contributions to the risk, independently from their ranking and expected issues – and is still too impractical in use.
- The risk informed approach which still needs extensive validation through a comprehensive application, which could be carried-out taking advantage from a plant operation change, such as the prolonged operation.

A great number of the existing standards and guidelines are not always applied worldwide. The Fukushima events demonstrated that this wide dispersion deserves attention. A first effort should be done to promote dissemination and

acceptance, suggesting the identification in the R&D reports of pre-normative entry data formatted to be easily integrated in the standard activities, supporting the participation in the research projects of experts having an experience of standard development in particular to prepare the formatted pre-normative entry data,

Ref [10] identifies that harmonisation of standards and practices is an issue that appears in several different fields, for example in safety assessment methods, safety margin methodology, component/material ageing predictions.

It is important that the lessons learned from the Fukushima accident contribute to the promotion of common practices. Standardisation of safety assessment and licensing will facilitate deployment of LWR technology all over Europe and abroad. A common set of qualified tools for safety analysis and advanced methodologies for the prediction of the consequences of extreme hazards should be developed. Use of data from Fukushima will provide a valuable source of validation material for these developments.

5.3.8 Inspection and Qualification

This technical area derives from the integration of the ENIQ Network and was added to NUGENIA recently. There is therefore not a specific NUGENIA Roadmap yet. The ENIQ Network dealt primarily with inspection techniques for defects and ageing of components with the two technical areas Qualification and Risk Assessment. Although the classical ENIQ work so far has not been directly linked to severe accidents, it is expected that technologies and methods can also be applied to areas relevant to Fukushima. This is particularly true for qualification methodologies for instrumentation and linking instrumentation and inspections to risk mitigation. The use of expert elicitation is another relevant area.

6. Conclusions

The objective of this report was to identify and outline research areas that need to be further strengthened in view of the lessons learned from the Fukushima accident. First of all it is important to stress that the Fukushima accident does not radically change the SRA of SNETP due to the fact that no completely new phenomena have been identified. Nevertheless it is clear that much stronger attention should be paid to research associated with safety issues. In particular more emphasis needs to be given to the assessment of robustness of the plant against extreme hazards, prevention and mitigation of severe accidents including organizational and societal factors.

The SNETP Fukushima Task Group has identified a series of “lessons learned” from the Fukushima accident, which can be grouped into four main areas:

- Nuclear system organization, safety infrastructure and safety culture.
- Assessment of risk from external events and prevention measures.
- Phenomenology, management and mitigation of severe accidents.
- Emergency preparedness and management.

Based on the assessment of the lessons learned, in chapter 4, R&D needs for thirteen specific research areas are presented with identification of more specific tasks, as follows:

1. Systematic assessment of vulnerabilities to defence-in-depth and safety margins for beyond design basis loads.
2. Human/organizational factors under high stress and harmful conditions.
3. Improved methods for external event hazard evaluation.
4. Use of the probabilistic methods to assess plant safety in relation to extreme events.

5. Advanced deterministic methods to assess plant safety in relation to extreme events.
6. Advanced safety systems for nuclear power plants
7. Advanced materials for nuclear power.
8. Advanced methods for the analysis of severe accidents.
9. Improved procedures for management of severe accidents.
10. Assessment of the radiological effects of the severe accidents.
11. Improved modelling of fuel degradation in the spent fuel pool.
12. Methods for minimization of contamination in the NPP surroundings and for treatment of large volume of radioactive waste.
13. Accident management in the framework of the integrated rescue system.

Examples of the specific tasks to be addressed in individual areas are given. These tasks are listed without specific classification or prioritization; it is clear that there are tasks of quite different nature. These include basic research, applied and pre-normative research, harmonisation of methods, investigation on organizational and societal issues, but also tasks focused on application of existing modelling tools.

The specific research needs and recommendations in chapter 4 are then incorporated into chapter 5 for a broader system overview, considering a number of horizontal areas as defined in the roadmap of NUGENIA association:

1. Plant Safety and Risk Assessment.
2. Severe Accidents.
3. Core and Reactor Operation.
4. Integrity Assessment and Ageing of System Structures and Components.
5. Fuel Development, Waste and Spent Fuel Management and Decommissioning.

6. **Innovative Gen III Design.**
7. **Harmonisation.**
8. **Inspection and Qualification.**

Although this report primarily addresses LWRs, many general implications and areas for additional research and development are applicable for other nuclear installations and reactor designs, including Gen IV reactors.

The Task Group recommends that, in the future revisions of the SNETP documents, a central position should be attributed to the safety problem as a whole, so that safety-oriented R&D becomes the overarching driving force and engine for the entire SNETP nuclear research agenda. It is also necessary that the research not only deals with understanding and modelling phenomena, but is strongly oriented towards deriving practical implications,

especially on prevention and mitigation devices which can improve safety .

The Fukushima accident had a large impact on the public view of nuclear energy and will impact the design and operation of nuclear reactors in the future. In spite of this fact, the accident didn't change the reasons for maintaining the role of nuclear power in the energy mix as sustainable, safe and low carbon source.

The R&D activities identified in the current document should continue playing an essential role in future utilization of nuclear power, supporting the life extension of the current LWRs, which should be associated with comprehensive safety assessment using up to date standards, the deployment of the Generation III reactors and the development of the Generation IV technologies, always keeping high safety level as utmost priority.

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Acknowledgements

We acknowledge the participants of the Gen II/III Technology Working Group and SARNET who defined the original R&D target areas, which formed the basis for this report.

We equally acknowledge the members of SNETP Governing Board and Executive Committee and other experts who provided a series of valuable contributions and comments.

ISBN 978-2-919313-05-1



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