# Safety review of worldwide nuclear power plants after the Fukushima Daiichi accident


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**Abstract:** The Fukushima Daiichi accident resulted from the concurrence of a loss of all electric power and a loss of the ultimate heat sink caused by extreme natural phenomena exceeding the design basis. This accident caused the meltdown of the reactor core at three units as well as the loss of the spent fuel pool cooling function. Therefore, this accident provided all countries that use nuclear power with the opportunity to embark on a reassessment of the safety and robustness of their nuclear power plants. The purpose of this paper is to investigate the safety reviews by international organizations and by individual countries within the limit of available information, and to clarify the safety related issues that are now common across the world. The result of these safety reviews indicates that there seems to be no concern about any nuclear power plant being the subject of another severe accident. It also becomes clear that there are effective measures that increase the robustness of nuclear power plants to beyond design basis events. The IAEA Action Plan on Nuclear Safety, which is the result of integrated expertise and knowledge from across the world, is considered to contain appropriate solutions for nuclear power plants.



**Keyword:** Fukushima Daiichi accident; IAEA Action Plan; safety review; stress test


## 1 Introduction

The Great East Japan Earthquake and the ensuing tsunami that occurred on March 11th 2011 caused the severe accident that was classified as level 7 on the International Nuclear and Radiological Event Scale (INES) at the Fukushima Daiichi nuclear power station (NPS). The reports on the Fukushima Daiichi accident followed significant concerns in the world and in particular in neighboring countries, regarding:

(1) the radiological effects to their citizens from the accident such as the radiation exposure of their citizens that were in Japan, the fallout of radioactive materials dispersing from Japan, the marine pollution from contaminated effluent water, the contaminated foods imported from Japan, to name but a few, and

(2) the safety and robustness of the nuclear power plants in their own countries.

The main subject of this paper is the latter concern.

When the Fukushima Daiichi accident occurred on March 11th 2011, 30 countries were operating 436 nuclear power units and were constructing 75 additional units, as shown in Table 1, indicating that the world's nuclear power generating output was significant. The Fukushima Daiichi accident resulted from the concurrent loss of all electric power and of the ultimate heat sink, caused by the extreme natural phenomena that exceeded the design basis. In the case of this accident, the meltdown of the reactor core at three units and the loss of the spent fuel pool cooling function were unlike the past Three Mile Island and Chernobyl accidents, which resulted from the defect of a safety design, from maintenance and from the respective man-machine systems. Therefore, all the countries in the world that promoted the development, construction and operation of nuclear power plants recognized that the Fukushima Daiichi accident was the one significant issue that had not been experienced or considered until then. These nuclear power countries embarked on a reassessment of the safety and robustness (*i.e.* safety review) of their nuclear power plants and took countermeasures as deemed necessary in light of the Fukushima Daiichi accident.

The purpose of this paper is to investigate the activities relating to the safety reviews by international organizations and by individual countries within the limit of available information such as their published national reports and data on their websites, and to clarify safety related issues that are common across the world and should be solved in


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the future. Unfortunately for this paper, some countries' information was fragmentary and other countries' data (marked with suffix "*" next to country name in Table 1) were not available to the author.

**Table 1 Number of units and output of nuclear power plants in operation and under construction in the world**

As of January 1, 2011

| Country | In operation: Units | In operation: Output 10MWe Gross | Under construction: Units | Membership | | | |
|---|---|---|---|---|---|---|---|
| U.S.A. | 104 | 10,524 | 1 | I | N | | W |
| France | 58 | 6,588 | 1 | I | N | E | W |
| Japan | 54 | 4,884 | 4 | I | N | | W |
| Russia | 28 | 2,419 | 11 | I | | | W |
| Germany | 17 | 2,152 | - | I | N | E | W |
| Korea | 20 | 1,772 | 6 | I | N | | W |
| Ukraine* | 15 | 1,382 | 2 | I | | | W |
| Canada | 18 | 1,323 | - | I | N | | W |
| U.K. | 19 | 1,195 | - | I | N | E | W |
| China | 13 | 1,085 | 30 | I | | | W |
| Sweden | 10 | 939 | - | I | N | E | W |
| Spain | 8 | 773 | - | I | N | E | W |
| Belgium | 7 | 619 | - | I | N | E | W |
| Taiwan* | 6 | 520 | 2 | | | | W |
| India | 19 | 456 | 8 | I | | | W |
| Czech | 6 | 397 | - | I | N | E | W |
| Switzerland | 5 | 341 | - | I | N | n | W |
| Finland | 4 | 282 | 1 | I | N | E | W |
| Brazil* | 2 | 201 | 1 | I | | | W |
| Bulgaria | 2 | 200 | - | I | | E | W |
| Hungary | 4 | 200 | - | I | N | E | W |
| Slovakia | 4 | 192 | 2 | I | N | E | W |
| South Africa | 2 | 188 | - | I | | | W |
| Romania | 2 | 141 | 3 | I | | E | W |
| Mexico* | 2 | 136 | - | I | N | | W |
| Argentina* | 2 | 101 | 1 | I | | | W |
| Slovenia | 1 | 73 | - | I | N | E | W |
| Netherlands | 1 | 51 | - | I | N | E | W |
| Pakistan* | 2 | 46 | 1 | I | | | W |
| Armenia* | 1 | 41 | - | I | | | W |
| Iran* | | | 1 | I | | | W |
| Total | 436 | 39,220 | 75 | | | | |

I: Member-state of IAEA
N: Member-state of OECD/NEA
E: Member-state of European Union (EU)
n: "neighboring country of EU" called in this paper
W: Country or industrial company belonging to a country member of WANO
*: No information was available to the author

The second chapter of this paper introduces the activities of international organizations (IAEA, NEA, WANO and INPO) that work with their member states and with multiple other partners worldwide to promote and support the safety of nuclear power plants. Chapters 3, 4, 5 and 6 introduce the perspective from which European and neighboring countries, the U.S.A., other countries and Japan implemented their safety reviews, and their respective results. Finally, chapter 7 summarizes the common safety related issues across the world.

## 2 Activity of international organizations after the accident

Immediately after the Fukushima Daiichi accident, international organizations (IAEA, NEA, WANO and INPO) embarked to collect and assess the information on the accident through dispatch of expert missions and other means, and supplied them to their member states and to their multiple other partners in order to support the safety reviews being conducted by each country. The activities of the international organizations and of nuclear power countries are chronologically summarized in Table 2.

### 2.1 International Atomic Energy Agency

The International Atomic Energy Agency (IAEA), under the United Nations umbrella serves to: (i) the planning and use of nuclear science and technology in its Member States, (ii) the development of nuclear safety standards, the achievement of a high level of safety, and the protection of human health and of the environment against ionizing radiation, (iii) implementing the Non-Proliferation Treaty and other non-proliferation agreements. In the case of the Fukushima Daiichi accident, the Department of Nuclear Safety and Security was responsible for the above mission (ii).

An international expert fact-finding mission was dispatched to Japan to identify the areas that needed further exploration and to assess safety issues linked to the Fukushima Daiichi accident. This mission's report was presented at the Ministerial Conference on Nuclear Safety, and was an important input for reviewing and strengthening the global nuclear safety framework [1]. Thereafter, under the declaration of the Ministerial Conference, the IAEA established a task force team and provided a Draft Action Plan on nuclear safety, which is a program to strengthen the global nuclear safety framework in light of the

**Table 2 Activity of international organizations and nuclear power countries**

| Date | Organization or Country | Activity |
|---|---|---|
| 2011 | | |
| March 11 | | The mega thrust earthquake and the ensuing tsunami caused the severe accident at the Fukushima Daiichi nuclear power station. |
| March 16 | China | The State Council announced that it would suspend approvals for new nuclear power plants and conduct comprehensive safety checks of all nuclear projects. |
| March 17 | U.S.A. | The President directed the NRC to implement comprehensive safety reviews of all nuclear power plants. |
| March 17 | Korea | The President ordered an across-the-board safety check. |
| March 24 - 25 | EU | The European Council declared that the safety of all EU nuclear power plants should be reviewed, on the basis of a comprehensive and transparent risk assessment “stress test”. |
| March | Japan | NISA indicated to the licensees the implementation of the immediate emergency measures. |
| March | WANO | Publication of SOER 2011, the report from the licensees' position. |
| April 20 | Canada | CNSC announced the establishment of an operational task force to evaluate the operational, technical and regulatory implications of the accident in relation to nuclear power plants. |
| May 4 | Korea | Publication of the report on the results of safety review. |
| May 5 | France | ASN required EDF to conduct a complementary safety evaluation. |
| May 13 | EU | The European Commission and ENSREG agreed to the adoption of stress test specifications prepared by WENRA. |
| May 13 | U.S.A. | NRC publicized the report by their inspectors. |
| May 17 | German | RSK presented the findings of the safety review to the public. |
| May 25 | Sweden | SSM ordered licensees to conduct renewed analysis of the plants’ resilience against different kinds of natural phenomena. |
| May 24 - June 2 | IAEA | Dispatched an international expert fact-finding mission to Japan. |
| June 1 | EU countries | Started stress tests. |
| June | Japan | Submitted the official report to IAEA. |
| June 20 - 24 | IAEA | Organized the Ministerial Conference on Nuclear Safety and presented the mission report. |
| June | IAEA | Established the Nuclear Safety Action Team |
| July 6 | Japan | NSC requested NISA to evaluate the comprehensive robustness to external events that exceed design assumptions. |
| July 12 | U.S.A. | NRC presented the special report “Recommendation for Enhancing Reactor Safety in the 21st Century”. |
| July | China | Received the Regulatory Review Service mission of IAEA. |
| August 15 | EU licensees | Presented progress reports. |
| August 31 | India | The committee concluded that the design, operating practices and regulations have inherent strengths, particularly in case of pressurized heavy water reactors. |
| September | Japan | Submitted the additional report to IAEA. |
| September 5 | IAEA | Authorized Action Plan on Nuclear Safety at the Board of Governors and endorsed it at the General Conference |
| September 15 | EU regulators | Provided progress reports. |
| October 31 | EU licensees | Presented final reports. |
| November 10 | IAEA | Reported the initial progress of Action Plan on Nuclear Safety to the Board of Governors. |
| November | INPO | Published INPO11-005, special report on the Fukushima Daiichi accident. |
| December 31 | EU regulators | Provided final reports. |
| December end | European Council | Assessed initial findings on the basis of a report from the European Commission. |
| 2012 | | |
| January 31 | IAEA | Completed the review of Japanese nuclear safety assessment process. |
| January - April | ENSREG | Implements peer reviews. |
| March 11 | IAEA | Revised the Memorandum between IAEA and WANO. |
| March 22 | IAEA | Organized international expert meeting. |
| June | ENSREG | Provides the consolidated report at the European Council meeting. |

Fukushima Daiichi accident. This work is addressed through twelve actions and their sub-actions as shown in Table 3. This Draft Action Plan was presented and authorized at the Board of Governors and at the General Conference [2]. The progress of the Action Plan on Nuclear Safety is to be reported to the Board of Governors [3]. Furthermore, the information on each action and the mission calendar are provided as a dashboard on the IAEA website [4] in order to effectively share all information on the Action Plan across the worldwide nuclear community. The mission calendar provides information on planned and completed missions, for example the Operational Safety Review Team (OSART) or the Integrated Regulatory Review Service (IRRS) among others. As information on missions becomes available, it will be added to the mission calendar.

**Table 3 Action Plan on Nuclear Safety**

| No | Title | Action |
|---|---|---|
| 1 | Safety Assessments | Undertake assessment of the safety vulnerabilities of nuclear power plants in light of the lessons learned from the accident to date |
| 2 | IAEA Peer Reviews | Strengthen IAEA peer reviews in order to maximize the benefits to Member States |
| 3 | Emergency Preparedness and Response | Strengthen emergency preparedness and response |
| 4 | National Regulatory Bodies | Strengthen the effectiveness of national regulatory bodies |
| 5 | Operating Organizations | Strengthen the effectiveness of operating organizations with respect to nuclear safety |
| 6 | IAEA Safety Standards | Review and strengthen IAEA Safety Standards and improve their implementation |
| 7 | International Legal Framework | Improve the effectiveness of the international legal framework |
| 8 | Member States Embarking on Nuclear Energy | Facilitate the development of the infrastructure necessary for Member States embarking on a nuclear power program |
| 9 | Capacity Building | Strengthen and maintain capacity building |
| 10 | Protection from Ionizing Radiation | Ensure the on-going protection of people and of the environment from ionizing radiation following a nuclear emergency |
| 11 | Communication | Enhance transparency and effectiveness of communication and improve dissemination |
| 12 | Research and Development | Effectively utilize research and development |

Reference: http://www.iaea.org/newscenter/focus/actionplan/

Under the Action Plan on Nuclear Safety, IAEA Member States embark on reassessments of their nuclear power plants' safety. An international expert meeting was organized to discuss and to identify all the relevant technical aspects of reactors and of the safety of spent fuel in light of the Fukushima Daiichi accident. The framework for IAEA peer reviews is being strengthened, for example through coordination between IAEA OSART missions and WANO peer reviews. The effectiveness of emergency preparedness and response arrangements, of IAEA safety standards and of the international legal framework are also being reviewed. The safety culture, the human resources management and the scientific and technical capacities in operating organizations are also being regularly reviewed. The IAEA is cooperating with Japan in the areas of monitoring, decontamination and remediation. Research and development is underway in areas highlighted by the accident, such as extreme natural hazards.

### 2.2 NEA, WANO and INPO

The membership of the Nuclear Energy Agency (NEA) consists of 30 countries in Europe, North America and the Asia-Pacific region, which account for approximately 85% of the world's installed nuclear capacity. The mission of the NEA is to assist its member countries in maintaining and further developing the safe, environmentally friendly and economical use of nuclear energy. The NEA works closely with the IAEA and with the European Commission.

Following the Fukushima Daiichi accident, the NEA is collecting information on activities undertaken nationally and internationally. It is also offering information on national response activities, stress tests reports, and complementary activities and assessments to the stress tests of the member countries, through its website [5].

The World Association of Nuclear Operators (WANO) unites every company and country in the world that has operating commercial nuclear power plants. The WANO pursues the safety and reliability of nuclear power plants worldwide by working together to assess benchmarks and to improve performance through mutual support, exchange of information and emulation of best practices. The Institute of Nuclear Power Operations (INPO), headquartered in Atlanta, U.S.A., is established by the plant operators and vendors in the world as a non-profit organization to promote the highest levels of safety and reliability in the operation of commercial nuclear power plants.

Both the WANO and the INPO published reports from the licensees' position, in order to share expertise and knowledge between operators and governments in light of the accident and to contribute to improvement in the safety of nuclear power plants, respectively[6, 7].

# 3 European Union and neighboring country

## 3.1 European Union

The European Union (EU) and neighboring country (indicated with "E" or "n" in the right column of Table 1, representing 148 units in operation, and equivalent to 34% of the world total) deployed a methodology with specifications towards European standardization. The European Council of March 2011 declared the following [8]:

"*The safety of all European Union nuclear plants should be reviewed, on the basis of a comprehensive and transparent risk and safety assessment ("stress tests"); the European Nuclear Safety Regulatory Group (ENSREG) and the Commission are invited to develop as soon as possible the scope and modalities of these tests in a coordinated framework in the light of lessons learned from the accident in Japan and with the full involvement of Member States, making full use of available expertise (notably from the Western European Nuclear Regulators Association, WENRA); the assessments will be conducted by independent national authorities and through peer review; their outcome and any necessary subsequent measures that will be taken should be shared with the Commission and within the ENSREG and should be made public; the European Council will assess initial findings by the end of 2011, on the basis of a report from the Commission.*".

The European Commission and the ENSREG developed the scope and modalities for assessments, and agreed to the adoption of stress test specifications prepared by the WENRA [9]. Stress tests started in June 2011 in a three-step process: (i) pre-assessment by the licensees, (ii) national report by the national regulatory authorities, and (iii) peer review by the multinational teams. After completing the peer reviews, the ENSREG will provide a consolidated report at the European Council meeting scheduled for June 2012. The European Commission is also in contact with countries outside the EU and is working with them on re-assessing their nuclear power plants. These are in particular Switzerland, Russia, Ukraine and Armenia.

### 3.1.1 Definition of the "stress tests"

The ENSREG define a "stress test" as a targeted reassessment of the safety margins of nuclear power plants. This reassessment consists of:

(1) evaluation of the response of a nuclear power plant when facing a set of extreme situations envisaged under "technical scope", and

(2) verification of the preventive and mitigation measures chosen from the defense in depth logic, against initiating events, consequential loss of safety functions, and severe accident management.

The technical scope of the stress tests is defined considering the issues highlighted by the Fukushima Daiichi accident, including the combination of initiating events and failures, because the existing safety analysis for nuclear power plants in the EU countries covers a large variety of situations. The technical scope of the EU "stress tests" focuses on (i) initial events, (ii) consequences of loss of safety functions from any initiating event conceivable at the plant, and (iii) severe accident management issues. As for initial events, design basis and evaluation of the margin are required to describe in detail according to the technical scope. Table 4 shows these requirements, summarized by the author.

The meaning of the word "cliff-edge effect" frequently used in Table 4 is, for instance, the exceeding point where significant flooding of the plant area starts after water overtopping a protection dike or exhaustion of the capacity of the batteries in the event of a station black out. This is to evaluate the robustness of the defense in depth approach and the adequacy of current accident management measures and to identify the potential for safety improvements, from both technical and organizational aspects.

**Table 4 Technical scope of the EU "stress tests"**

| | | |
|---|---|---|
| 1. Initiating events | | |
| (1) Earthquake | - | Level of design basis earthquake (DBE) |
| Design basis | - | Methodology to evaluate DBE |
| | - | Adequacy of design basis |
| | - | Identification of safety related structures, systems and constructions (SSCs) |
| | - | Operating provisions to prevent reactor core damage |
| | - | Indirect effects including failure of SSCs, loss of external power supply and situation outside NPP |
| | - | Plant compliance with current licensing basis |
| Evaluation of the margin | - | Weak points and cliff edge effects according to earthquake severity |
| | - | Provisions to prevent cliff edge effects or to increase robustness of plant |
| | - | Range of earthquake severity without losing confinement integrity |
| | - | Failure modes leading to unsafe plant condition |
| (2) Flooding (including tsunami and bad weather conditions) | - | Level of design basis flood (DBF) |
| | - | Methodology to evaluate DBF |
| | - | Adequacy of design basis |
| Design basis | - | Provisions to maintain water intake function and emergency electrical power supply |
| | - | Operating provisions to mitigate flooding effect |
| Evaluation of the margin | - | Level of flooding without severe damage to fuel |
| | - | Time margin to implement additional protective measures |
| 2. Loss of electrical power and loss of the ultimate heat sink | | |
| (1) Loss of off-site power (LOOP) | - | Time to operate on-site power source without any external support |
| | - | Provisions to prolong time of on-site power supply (refueling of diesel generators, *etc*.) |
| | - | Provisions to increase plant robustness (steam driven pumps, *etc*.) |
| (2) Loss of off-site power and of on-site backup power sources (SBO) | - | Battery capacity and duration |
| | - | Time to withstand SBO without any external support before unavoidable severe damage of fuel |
| | - | External actions to prevent fuel degradation |
| | - | Provisions to prevent cliff edge effects or to increase plant robustness |
| (3) Loss of primary ultimate heat sink (UHS) | - | Provisions to prevent loss of UHS (various water intakes for primary UHS, *etc*.) |
| | - | Time to withstand UHS without any external support before unavoidable severe damage of fuel |
| | - | External actions to prevent fuel degradation |
| | - | Provisions to prevent cliff edge effects or to increase plant robustness |
| (4) Loss of primary UHS with SBO | - | Time to withstand loss of main UHS + SBO without any external support before unavoidable severe damage of fuel |
| | - | External actions to prevent fuel degradation |
| | - | Provisions to prevent cliff edge effects or to increase plant robustness |
| 3. Severe accident management | | |
| (1) At stage of loss of core cooling function | - | Measures before/after occurrence of fuel damage in reactor vessel |
| | - | Measures after failure of reactor vessel |
| (2) After occurrence of fuel damage | - | Prevention of $H^2$ deflagration or $H^2$ detonation |
| | - | Prevention of over pressurization of containment |
| | - | Prevention of re-criticality |
| | - | Prevention of basement melt through |
| | - | Electrical AC/ DC power and compressed air for protecting containment integrity |
| (3) At stage of loss of containment integrity | - | Measures to mitigate consequences of loss of containment integrity |
| (4) At stage of loss of core cooling function in fuel storage | - | Measures before/after losing adequate shielding against radiation |
| | - | Measures before/after occurrence of uncovered fuel in pool |
| | - | Measure before/after occurrence of fuel degradation in pool |
| For(1), (2), (3) and (4) | - | Identification of cliff edge effect and evaluation of time margin |
| | - | Assessment of adequacy of existing management measures |
| | - | Organization of the licensee to manage situation |
| | - | Possibility to use existing equipment, *etc*. |
| | - | Evaluation of extensive destruction of infrastructure around NPP, *etc*. |

Reference: ENSREG, Annex I "EU Stress tests specifications" Modified by author.

3.1.2 Process to perform the "stress test"

First the licensees perform the reassessments and issue licensees' reports to their regulatory authority. Then regulatory authorities independently review them and publish national reports. The main purpose of national reports is to draw conclusions from licensees' assessment using the EU "stress tests" specifications. The national reports are subjected to a peer review process to enhance the credibility and accountability of the process.

Both national reports and the results of peer reviews are made public. The results of reviews are also discussed in national and European public seminars. Such full transparency is thought to contribute to the EU "stress test" being acknowledged and trusted by European citizens.

**3.2 France**

The French approach to conduct complementary safety assessments (CSAs) of nuclear power plants, in compliance with a request letter from the Prime Minister, meets the expectations of the EU Council conclusions and is consistent with the specifications of the EU stress tests. The CSAs were implemented for 59 nuclear power plants in service or under construction by the Electricité de France (EDF). First, the EDF provided their comprehensive and consolidated report. Subsequently, the French Nuclear Safety Authority (ASN) reviewed this report with the support of the Institute of Radiation Protection and Nuclear Safety (IRSN).

Following the CSAs performed on nuclear power plants, the ASN concluded the following [10, 11]:
"*These plants offer a sufficient safety level to require no immediate shutdown of any of them. At the same time, their continued operation requires an increase in their robustness to extreme situations beyond their existing safety margins, as soon as possible.*"

The ASN underlined the importance of the following measures as described below in individually:

(1) The "hard core" of material and organizational measures - The "hard core" comprises strengthened equipment including an electricity generating set and emergency cool down water supply to cope with the prolonged loss of electrical power supplies or loss of cooling systems, crisis management premises and equipment, means of communication and alert, technical and environmental monitoring instrumentation, and operational dosimetry resources for workers.

(2) "Nuclear rapid response force (FARN)" - The FARN, comprising specialist crews and equipment, is able to take over from the personnel of a site affected by an accident and deploy additional emergency response resources in less than 24 hours with operations beginning on the site within 12 hours.

(3) Implementation of complementary strengthened measures for the spent fuel storage pools to reduce the risk of exposure of the fuel.

(4) Feasibility studies, such as a geotechnical containment system, designed to protect the groundwater and surface water in a severe accident.

(5) Examinations of strengthening the venting filtration device on the reactor containments to improve both its robustness and its effectiveness.

The ASN identified the following social, organizational and human factors: (i) renewal of the licensee workforces and skills, (ii) organization of the use of subcontracting, and (iii) research on the above topics.

In addition, the ASN will focus on learning the lessons from the results of the European peer review process. It will continue to participate actively in all the analyses being conducted worldwide to gain a clearer understanding of the Fukushima Daiichi accident and learn all relevant lessons.

**3.3 Germany**

The Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) asked the regulatory authorities to initiate the EU stress tests according to the ENSREG Declaration. The stress tests of 17 nuclear power plants, including 8 aged plants forced to permanently shut down, were implemented. The results were compiled generically for all plants by the Reactor Safety Commission (RSK) [12].

The licensees reported no shortfalls regarding safety precautions for nuclear power plants participating in the EU stress tests. Likewise, no cliff edge effects were detected. However, the regulatory authority suggested the following potential safety improvements and further work forecasted:

(1) Continuation of the RSK work program related in particular to station blackout, loss of off-site power, loss of service water supply, accident management measures, and aircraft crash.
(2) Further address the regulatory implications to reflect the results of defense in depth analysis and assessments of the Fukushima accident.
(3) Licensee information notice containing an analysis of the Fukushima accident for potential applicability of individual aspects to German plants.
(4) Update of the higher level nuclear rules and regulations of the BMU.
(5) Publication of “Safety Requirements for Nuclear Power Plants” is expected in 2012.
(6) Ongoing updates of the safety standards of the Nuclear Safety Standards Commission.

Furthermore, the licensees were required to perform safety retrofits and improvements. The list of retrofit measures compiled by BMU is being continued and updated with the analysis of the Fukushima Daiichi accident and the results of the EU stress tests. Implementation of the identified safety improvements will be dealt with within the regulatory licensing and oversight process.

### 3.4 United Kingdom [13]

The Office for Nuclear Regulation (ONR) was content with the adequacy of the EU “stress tests” program undertaken by the licensees, and of the licensee reports. The ONR expected that the enhancements identified to strengthen resilience would be implemented within an appropriate timescale and would provide a positive contribution to nuclear safety in the U.K. in the case of a significant beyond design basis event. The ONR also expected the licensees to develop improved approaches to beyond design basis events and to apply these approaches to confirm that the resilience enhancements underway are sufficient, or to further strengthen the current proposals. These expectations by the ONR are summarized as follows:

(1) Key provisions enhancing robustness - The periodic safety review (PSR) is performed against the latest safety standards and technical knowledge. If PSR identifies any reasonably practicable safety improvements, these should be made by the licensee. The PSR includes the safety review in response to events such as earthquakes, floods, fire and explosion.
(2) Safety issues - Further work will be needed by the licensees to achieve a consistent standard for beyond design basis external hazards. In addition, some aspects of the reviews for beyond design basis external hazards will need to be extended when more robust methodologies will have been developed.
(3) Potential safety improvements and further work forecasted - The potential for enhancements to safety margins assessment methods (*e.g.* passive hydrogen re-combination in the containment and containment venting during station blackout (SBO), flood resilience enhancements, improvements to fuel pond cooling make-up, and provision of additional emergency backup equipment) is being considered.

The ONR welcomes the opportunity to participate in and be subject to the peer review process. The ONR expects that this will provide a further independent opportunity to learn any issues arising or already applied in other European states. The peer review process should also help provide assurance that the U.K. nuclear site licensees and the independent nuclear safety regulator have applied the EU stress tests appropriately.

### 3.5 Sweden [14]

The Swedish Radiation Safety Authority (SSM) ordered the licensees of the nuclear power plants to conduct renewed analyses of the facilities’ resilience against different kinds of natural phenomena. They were also to analyze how the facilities would be capable of dealing with a prolonged loss of electrical power, regardless of the cause.

After the TMI accident in 1979, all Swedish NPPs installed containment filtered vents (CFV) with an inerted multi-venturi scrubber system as shown in Fig.1, to withstand a core meltdown accident without any casualties or ground contamination. The CFV design scenario is station blackout, loss of all AC and loss of steam-driven pumps, with no manual actions credited during the first 8 hours. They are also able to withstand external events such as extreme weather, which includes rain, wind, sea water level, outdoor temperature and lightning.

During the loss of off-site power and of ordinary/alternate back-up AC power source, all Swedish NPPs rely on different types of mobile equipment located at the sites. However, the stress tests showed that the number of available mobile units at the sites is not sufficient, in particular in the case of simultaneous events at more than one unit. In addition, it shows that some plants have not been fully verified to safely shut down and to maintain safe shut down conditions in case of blockage of the cooling water intake.

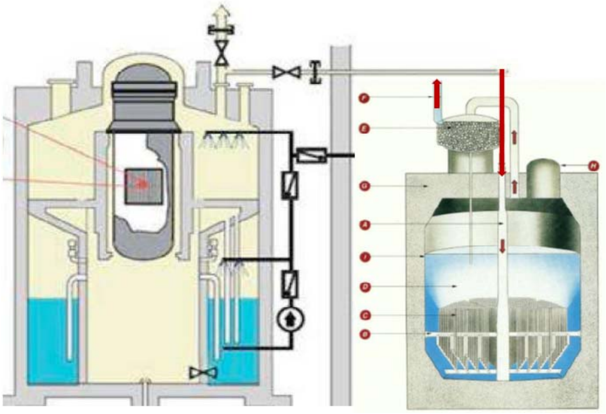

Fig.1 Containment filtered vent with an inerted multi-venturi scrubber system

This figure was synthesized by the author from the original figures (Figs. 1.2 and 1.4) in the reference [14].

### 3.6 Finland [15]

The Ministry of Employment and the Economy asked the Radiation and Nuclear Safety Authority (STUK) to report on the preparedness of nuclear power plants to floods and other extreme natural phenomena and their effect to the functioning of the power plants. STUK stated that although there is no need for immediate safety improvements, there is reason for power companies to continue investigations into preparation for certain exceptional natural conditions.

The original design of the operating NPPs in Finland did not take into account all possible aspects of weather phenomena or their possible combinations. Therefore, some further changes will be made at the operating NPPs based on the stress tests. The stress tests also suggested the undertaking of seismic studies to confirm adequate robustness of certain vital structures such as the spent fuel pool structures.

## 4 United States of America

As for the U.S.A, which has the greatest nuclear capacity with 104 units in operation (equivalent to 24% of all units in the world), the President directed the Nuclear Regulatory Commission (NRC) to implement comprehensive safety reviews of all nuclear power plants with the lessons learned from the Fukushima Daiichi accident. Under the direction, a Task Force was established to conduct a systematic and methodical review of NRC processes and regulations, to determine whether the agency should make additional improvements to its regulatory system and to make recommendations to the NRC as regards its policy direction. The Task Force studied the manner in which the NRC has historically required protection from natural phenomena and how the NRC has addressed events that exceed the current design basis following the TMI accident in 1979 and the terrorist attack of September 11th 2001. Consequently, it concluded that a sequence of events like the Fukushima Daiichi accident is unlikely to occur in the U.S.A. Some appropriate mitigation measures have been implemented, reducing the likelihood of core damage and radiological releases. However, it also concluded that a more balanced application of the NRC's defense in depth philosophy using risk insights would provide an enhanced regulatory framework that is more logical, systematic, coherent, and better understood. Such a framework would support appropriate requirements for increased capability to address events of low likelihood and high consequence, thus significantly enhancing safety.

The Task Force referred to the revision of the SBO rule (*i.e.* each nuclear power plant must be able to cool the reactor core and maintain containment integrity for a specified duration as a complete loss of required onsite and off-site AC electrical power) to: (i) establish a minimum coping time of 8 hours for a loss of all AC electrical power, (ii) establish the equipment, procedures, and training necessary to implement an "extended loss of all AC" coping time of 72 hours for core and spent fuel pool cooling and for reactor coolant system and primary containment integrity as needed.

It also referred to the need for hardened vents at BWRs with Mark II containments whose volume is approximately 25 percent larger than that of Mark I ones. Eight BWR units in the U.S.A. have Mark II containment designs. Three of these units have installed hardened vents, and the remaining five units, at three sites, have not yet installed hardened vents.

The recommendations by the Task Force are referred below from the reference [16]:

*(1) establishing logical, systematic and coherent regulatory framework for adequate protection that appropriately balances defense in depth and risk considerations.*

*(2) that the NRC require licensees to re-evaluation and upgrade of the design basis seismic and flooding protection of structures, systems, and components.*

*(3) potential enhancements to the capability to prevent or mitigate seismically induced fires and floods,*

*(4) that the NRC strengthen station blackout mitigation capability at all operating and new reactors for design basis and beyond design basis external events.*

*(5) requiring reliable hardened vent designs in boiling water reactor plants with Mark I and Mark II containments.*

*(6) that the NRC identify insights about hydrogen control and mitigation inside containment or in other buildings.*

*(7) enhancing spent fuel pool makeup capability and instrumentation for the spent fuel pool.*

*(8) strengthening and integrating emergency plans address prolonged station blackout and multiunit events.*

*(9) that the NRC require that facility on-site emergency response capabilities such as emergency operating procedures, severe accident management guidelines, and extensive damage mitigation guidelines.*

*(10) that the NRC pursue additional emergency preparedness topics related to multiunit events and prolonged station blackout.*

*(11) that the NRC should pursue emergency preparedness topics related to decision making, radiation monitoring, and public education.*

*(12) that the NRC strengthen regulatory oversight of licensee safety performance by focusing more attention on defense in depth requirements.*

## 5 Other countries

Other nuclear power countries (equivalent to 130 units, 30% of all units in the world) embarked on safety reviews of nuclear power plants by their regulatory authorities or with the cooperation of international organizations, respectively.

### 5.1 Russia [17]

Russia implemented a licensing safety review and evaluation of VVER and RBMK after the Chernobyl accident, getting the support of international experts. After the Fukushima Daiichi accident, she implemented a self-appraisal of the emergency power supply, the hydrogen explosion prevention, earthquake proof, emergency core cooling system, radiation monitoring, accident management and safety analysis in an emergency situation, at all the power plants.

Russia decided to (i) promptly implement the emergency exercise without delay, (ii) within a year, specify the additional water source for the residual heat removal and implement the analysis of the influence of earthquakes and of the accident management, (iii) within two years, install any additional facilities and upgrade the emergency procedure, and (iv) within five years, complete the introduction of the additional design solutions.

### 5.2 Korea [18, 19]

The government decided to conduct a comprehensive special safety inspection of nuclear power plants. The regulatory authority indicated the principles for the inspection as follows:

(1) Confirm safety against design basis earthquake and coastal flooding,

(2) Secure cooling capability of the nuclear reactor even against inundation of the power system on the premise of occurrence of natural hazards exceeding the design basis,

(3) Secure the integrity of the containment building in case of severe accidents, assuming loss of reactor cooling functions,
(4) Reinforce the capability of emergency response assuming large emission of radioactive substances, and
(5) Perform an accurate inspection of aging nuclear power plant in terms of age-related deterioration and sudden shutdown.

As a result of this inspection, the regulatory authority concluded that Korean nuclear power plants are safe for expected maximum potential earthquakes and coastal flooding based on the investigation and research to date. However, regulatory authority pointed out the following concerns:
(1) Investigate and research the maximum potential of earthquakes,
(2) Reinforce the intake ability of equipment cooling water intake pump,
(3) Confirm the integrity of electric power, cooling and fire protection system when inundation occurs,
(4) Install one alternate diesel generator per 2 or 4 units to cope with SBO,
(5) Secure the multiple cooling sources for spent fuel pool,
(6) Install ventilation or depressurizing facilities in the containment buildings, and
(7) Prevent the deterioration of safety margins due to aging.

### 5.3 Canada [20]

The Canadian Nuclear Safety Commission (CNSC) decided the establishment of an operational task force to evaluate the operational, technical and regulatory implications of the Fukushima Daiichi accident in relation to Canadian nuclear power plants. The task force reviewed licensees' responses to re-examine the safety of their nuclear power plants, the underlying defense in depth against external hazards, severe accident scenarios and emergency preparedness procedures and guidelines. The task force reported the short and long-term measures to address any significant gaps at Canadian nuclear power plants and recommended potential changes to CNSC regulatory requirements, inspection programs and policies for the existing CANDU reactors and for the possible new nuclear power plants.

### 5.4 China [21]

The State Council announced that it would suspend approvals for new nuclear power plants and conduct comprehensive safety checks of all nuclear projects in order to learn the lessons from the Fukushima Daiichi accident, particularly regarding siting of reactors with plant layout and control of radiative release. After three months, the inspection of operating plants had been completed, and review of plants under construction was completed by October in 2011.

In May in 2011, some supplementary safety measures were announced. A new China National Plan for Nuclear Safety with short, medium and long-term actions was being formulated, and approval for new plants was suspended until the Plan's approval.

In July 2011, the Regulatory Review Service mission of the IAEA carried out its review of China's regulatory framework for nuclear safety. It made a number of recommendations but said that the review had provided "confidence in the effectiveness of the Chinese safety regulatory system and the future safety of the vast expanding nuclear industry".

### 5.5 India

The Atomic Energy Regulatory Board (AERB) created a committee to review the safety of nuclear power plants against external events of natural origin, in light of the Fukushima Daiichi accident. The committee concluded as follows [22]:
"*The design, operating practices and regulations have inherent strengths, particularly in case of pressurized heavy water reactors (PHWR) that account for 18 out of the 20 currently operational nuclear power plant units in India, to deal with the natural events and their consequences. The interim safety measures had already been taken to enhance the safety of 2 older BWR units. These measures include provisions for continuous reactor cooling under prolonged station black out, in which loss of both off-site and on-site power supplies is considered and preparatory work for inerting the containment with nitrogen to avoid hydrogen explosions.*"

# 6 Japan

Japan, with 54 units, equivalent to 12% of all units in the world, and as the country that directly experienced the Fukushima Daiichi accident, is tackling emergency safety measures at nuclear power plants, in an effort led by its government. Immediately after the Fukushima Daiichi accident, the regulatory authority, the Nuclear and Industrial Safety Agency (NISA) requested of the 9 electric power companies (nuclear power plant operators) the implementation of immediate emergency measures. Afterwards, NISA would verify that the immediate emergency measures including the counter measures of all AC power loss and others would be implemented, and that the mid and long-term measures will be appropriately implemented according to the action plan. It also evaluated that severe accident managements reported by the electric power companies were appropriately implemented, through on-site inspections. But at the same time, the Nuclear Safety Commission requested NISA to evaluate the comprehensive robustness to external events that exceed design assumptions in the existing nuclear power plants. And the government decided that the safety of nuclear power plants should be confirmed by the results of comprehensive safety assessments (*i.e.* “Japanese stress test”). The specification of the “Japanese stress test” prepared by NISA differs from EU stress test specifications in several ways. Its focus on initial events, consequences of loss of safety functions and severe accident management are the same. However, it consists of a two-stage evaluation: preliminary assessments focusing on restarting plants after periodic inspections, and secondary assessments for all plants [23].

This comprehensive safety assessment is underway, while Japan is hosting an international seminar, which consists of experts and of the IAEA mission. In the Fukushima accident, the safety related structures, systems and components (SSCs), such as emergency diesel generators, were damaged and flooded by the tsunami due to the inadequate preparedness. Therefore, preventive measures against the tsunami at nuclear power plants are top agenda for Japan. Some operators began the boring exploration to examine the traces of tidal bore in the past. They gather soil and stone and specify the existence or non-existence thereof, and the period of marine creatures that resulted from any tsunami. Power supplies, reliable cooling function of reactors and spent fuel pools, and water tightness of SSCs are also being reviewed. In addition, enhancement of measures to prevent hydrogen explosions, the radiation exposure management system, and training for responding to severe accidents are being discussed.

Moreover, the Nuclear Emergency Headquarters (NEHQ) of the Japanese Government continues to follow the 28 learned lessons, classified into five categories: 1) prevention of severe accidents occurrence, 2) countermeasures to manage severe accidents, 3) institution to nuclear emergencies, 4) enhancement of safety infrastructure and 5) thoroughly fostering a safety culture, indicated in the official report to the IAEA [23-25].

# 7 Summary

The Fukushima accident was caused by an extreme natural phenomenon, unlike the past Three Mile Island and Chernobyl accidents. Therefore, this accident provided all nuclear power countries with the opportunity to embark on a reassessment of the safety and risks of their nuclear power plants. France, Germany, the U.K., Sweden and Finland are implementing stress tests by the standardized EU specifications. In the U.S.A., a Task Force carried out the systematic and methodical review of NRC processes and regulations. Russia, Korea, Canada, China and India conducted safety reviews or safety checks mainly by their regulatory authorities. As for Japan, a unique stress test is in progress, to verify the robustness of nuclear power plants.

The result of these safety reviews indicates that there seems to be no concern as regards potentially severe and immediate accidents at any nuclear power plant. However, it also becomes clear that there are effective measures to be implemented that increase the robustness of nuclear power plants against the beyond design basis events.

The measures common to all countries are as follows:

- Arranging the alternate electrical power supply and alternate UHS,
- Increasing the capability of cooling function of reactor and spent fuel pool, and

- Strengthening SSCs from perspective of defense in depth requirements.

The individual measures for every country are as follows:

- Creating FARN, in France,
- Installing CFV for BWR, in Sweden,
- Revising SBO rule, in U.S.A.,
- Preventing the deterioration of safety margins due to aging, in Korea, and
- Re-examining the natural disaster in the past, in Japan.

The appropriate solutions to the above subjects seem to be efficiently and effectively obtained through worldwide cooperation. To this end, the IAEA Action Plan on Nuclear Safety, with its integrated worldwide expertise and knowledge is considered the most valuable resource.

## Nomenclature

| | |
|---|---|
| AC | Alternate Current (Electrical Power) |
| AERB | India: Atomic Energy Regulatory Board |
| ASN | France: Nuclear Safety Authority |
| BMU | Germany: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety |
| BWR | Boiling Water Reactor |
| CANDU | Canadian Deuterium Uranium (Reactor) Canadian-designed Pressurized Heavy Water Reactor |
| CFV | Sweden: containment filtered vent |
| CNSC | Canadian Nuclear Safety Commission |
| CSA | France: Complementary Safety Assessment |
| DF | Decontamination Factor |
| EDF | France: Electricité de France |
| ENSREG | European Nuclear Safety Regulatory Group |
| FARN | France: Nuclear rapid response force |
| IAEA | International Atomic Energy Agency |
| INES | International Nuclear and Radiological Event Scale |
| INPO | Institute of Nuclear Power Operation |
| IRSN | France: Institute of Radiation Protection and Nuclear Safety |
| MVSS | Sweden: multi-venturi scrubber system |
| NEA | Nuclear Energy Agency |
| NEHQ | Nuclear Emergency Headquarters |
| NISA | Japan: Nuclear and Industrial Safety Agency |
| NRC | U.S.A.: Nuclear Regulatory Commission |
| ONR | U.K.: Office for Nuclear Regulation |
| OSART | IAEA: Operational Safety Review Team |
| PSR | Periodic Safety Review |
| PWR | Pressurized Water Reactor |
| RBMK | Reaktory Bolshoi Moshchnosti Kanalynye Russian-designed Hi-power Pressure Tube Reactors |
| RSK | Germany: Reactor Safety Commission |
| SBO | Station Black Out |
| SSCs | Structures, Systems and Components |
| SSM | Sweden: Swedish Radiation Safety Authority |
| STUK | Finland: Radiation and Nuclear Safety Authority |
| TMI | Three Mile Island |
| UHS | Ultimate Heat Sink |
| VVER | Vodo-Vodyanoi Energetichesky Reactor Russian-designed Pressurized Water Reactor |
| WANO | World Association of Nuclear Operators |
| WENRA | Western European Nuclear Regulators Association |

## References

As to the sources of information, the author utilized many references mainly retrieved from the internet. The utilized sources are listed classified into international organizations and countries.

IAEA

[1] IAEA International Fact Finding Expert Mission of the FUKUSHIMA Daiichi NPP Accident following the Great East JAPAN Earthquake and Tsunami, June 16, 2011

[2] GOV/2011/59-GC(55)/14, Draft IAEA Action Plan on Nuclear Safety, September 5, 2011

[3] GOV/INF/2011/15, Initial Progress in the implementation of the IAEA Action Plan on Nuclear Safety, November 10, 2011

[4] http://www.iaea.org/newscenter/focus/actionplan

OECD/NEA

[5] http://www.oecd-nea.org/

WANO

[6] SOER 2011, Fukushima Daiichi Nuclear Station Fuel Damage Caused by Earthquake and Tsunami, March 2011 (not publically available)

INPO

[7] NPO11-005, Special Report on the Nuclear Accident at the Fukushima Daiichi Nuclear Power Station, November 2011

EU

[8] ENSREG: EU Stress Tests Specifications, 2011

[9] WENRA: Stress Test Specifications Proposal by the WENRA Task Force, April 21, 2011

France

[10] ASN: Complementary Safety Assessments of French nuclear power plants, December 2011

[11] ASN: ASN opinion n° 2012-AV-0139 of 3 January 2012 concerning the complementary safety assessments of the priority nuclear facilities in the light of the accident that occurred at the nuclear power plant of Fukushima Daiichi, January 3, 2012

Germany

[12] BMU: EU Stress Test National Report of Germany, December 2011

UK

[13] ONR: European Council “Stress Tests” for UK nuclear power plants - National Final Report, December 2011

Sweden

[14] European stress tests, The Swedish National Report for nuclear power plants December 29, 2011

Finland

[15] European stress tests for Nuclear Plants, National Report, December 30th, 2011

U.S.A.

[16] NRC: Recommendation for Enhancing Reactor Safety in the 21st Century - The near-term task force review of insights from Fukushima Dai-ichi Accident, July 12, 2011

Russia

[17] International Nuclear Safety Symposium on the accident of Fukushima Dai-ichi NPS, October 31 to November 1, 2011 in Japan

Korea

[18] Report on the Results of the Safety Review for Domestic Korean Nuclear Power Plants, May 4, 2011

[19] Policy Issue 0 - Report of the Korean Government Response to the Fukushima Daiichi Nuclear Accident

Canada

[20] CNSC: INFO-0824, Fukushima Task Force Report, October, 2011

China

[21] http://www.world-nuclear.org

India

[22] AERB: Press release Report of high level AERB committee on safety review of Indian nuclear power plants against external events of natural origin, September 5, 2011

Japan

[23] IJNS Editor: Addenda to the second update of the Fukushima Daiichi NPS accident, IJNS vol.2, No.3, September, 2011: 212-225

[24] NEHQ: Report of the Japanese Government to the IAEA Ministerial Conference on Nuclear Safety - The Accident at TEPCO’s Fukushima Nuclear Power Stations, June 2011

[25] NEHQ: Additional Report of the Japanese Government to the IAEA - The Accident at the Tokyo Electric Power Company Inc. (TEPCO) Fukushima Daiichi NPS, September 2011