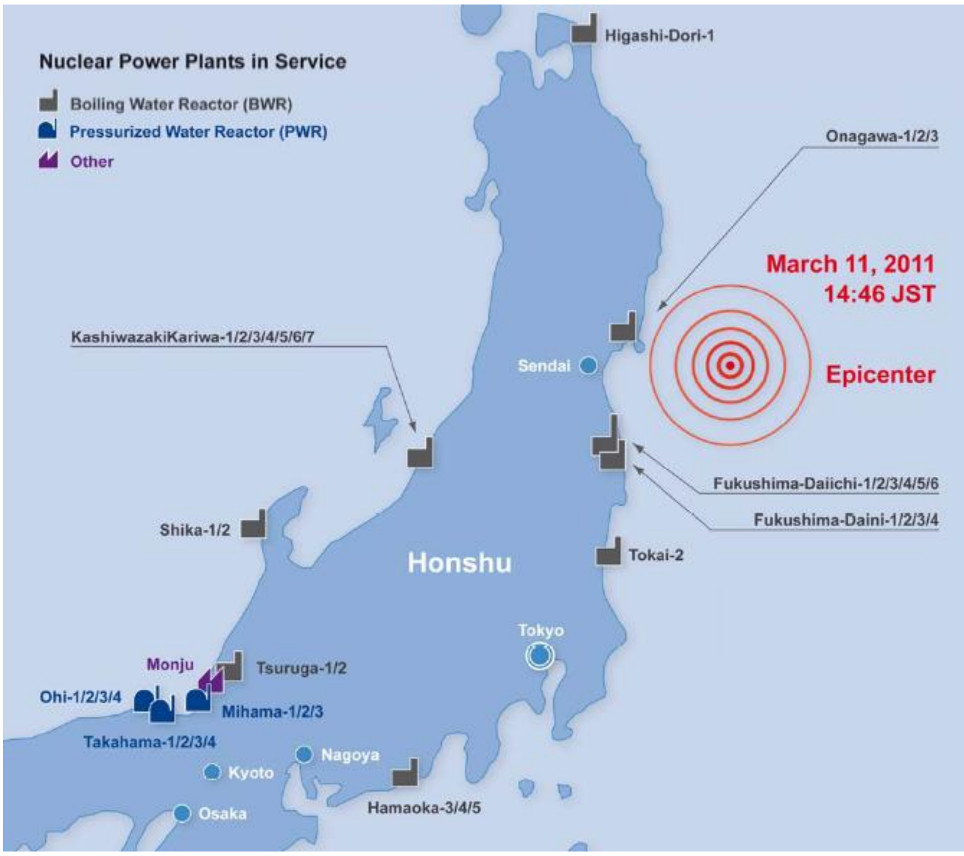
Independent Technical Evaluation and Review

Fukushima Daiichi Nuclear Accident
First considerations

Preliminary Report



May 2011

Fukushima Daiichi Nuclear Accident
Preliminary Report

Executive Summary

The **Tohoku earthquake** with magnitude 9.0 stroke the east coast of Japan at 14.46 on Friday 11 March and the generated tsunami hit the coast soon after in a time delay of about 20 minutes.
Eleven reactors at four nuclear power plants in the region were operating at the time: Fukushima Daiichi 1, 2, 3, Fukushima Daini 1, 2, 3, 4, Onagawa 1, 2, 3, and Tokai Daini 1 for a total amount of 9377 MWe. All, as required, shut down automatically when the quake hit.

The earthquake, whose epicenter was 130 miles east north east from the site of the Fukushima-1 (Daiichi), was a complex double quake of a severe duration of about 3 minutes. Japan moved a few meters east and the local coastline subsided half a meter.
The exceptional duration of the Tohoku event has characterized its destructive power although the recorded peak ground accelerations appear not so much higher compared to those caused by other seismic events with lower magnitude.

All 6 units in Fukushima Daiichi NPP are boiling water reactor (BWRs) designed more than 40 years ago. After the earthquake all units were powered from backup emergency Diesel Generators (D/G), started automatically after the loss of offsite power due to the seismic event.
The D/Gs, replacing the lost offsite power, ensured the cooling functions for the reactors, for the spent fuel pools of each reactor and for the site central spent fuel pool.

About one hour after the quake (15.41) the onsite electrical emergency power was lost due to the tsunami (14 m wave high) that destroyed the sea water intakes and overwhelmed the plants' physical structures, causing inundation, wetting of many components and making many areas inaccessible.
The resulting accident event was a ‘’**total station blackout’’** for units 1, 2, 3 and 4 together with the loss of the ultimate heat sink.
In fact 12 out of 13 back-up D/Gs on site, located in the basements of the turbine buildings, were disabled. Only one air-cooled D/G (all others were seawater-cooled) was able to supply electrical power to units 5 and 6, which remained under full control after some initial troubles.

The batteries ensured the supply of some essential loads for a certain time, after a few hours the dc-power was also lost and the control rooms remained practically unavailable and in the dark.
Following the station blackout some cooling of the core in the shutdown reactors was apparently maintained through steam driven cooling system which operated, based on available data, very short time for unit 1, about 1,5 day for unit 3 and about 3 days for unit 2.
When the cooling function was completely lost the reactors overheated. This resulted in pressurization of primary circuit, discharge of steam through safety relief valve to the suppression pools, pressurization of primary containment, need to vent and consequent several disruptive explosions because of accumulation of H2, produced by oxidation of overheated fuel zirconium cladding in steam reach environment.
The same overheating happened to the spent fuel pond in unit 4 (with significant load of used fuel assemblies).

Major releases of radionuclides to the environment occurred: initially in air but later also as leakage to the sea.

The operators struggled to restore control by injecting sea-water (with mobile pumps) in the reactor vessel of unit 1, 2 and 3 and trying to replenish (discharge of water from helicopter or water spray on the top of the buildings) the water in the spent fuel pond of all units 1 to 4.
In order to limit the problems created with salt deposition and corrosion, the injection of seawater was successfully replaced by fresh water from a nearby dam on March 25
Connection of the units to external electrical power, made available via cable onsite, started on March 22. One by one in a few days the lighting and the power to the control rooms of unit 3 first and then of units 1, 2 and 4 were restored.

The situation at the time of writing is that in units 1, 2 and 3 the fuel is damaged with suspected relocation of part of it, but essentially contained, the cooling is still ensured by an ‘’open circuit’’ using fresh water and pump trucks with heat released through evaporation of water. Work continues onsite to establish a stable heat removal path to external heat sinks. The primary containment of unit 1 is flooded at a level corresponding to the upper part of the reactor core.

The initial rating of the accident (according to the International Nuclear Event Scale (INES) of the International Atomic Energy Agency (IAEA) was level 4. On March 18 the Japan Nuclear Safety Authority (NISA) raised the severity to level 5, and on April 12, based on the estimated release of radioactive substances, NISA announced a new provisional rating of Level 7 (the maximum).

The Japanese authorities soon declared the nuclear emergency on the evening of March 11, issued a first evacuation order for people within 2 km, extended later to 3 km, then at 05.44 on March 12 to 10 km and at 18.25 of the same day to 20 km, along with other countermeasures. Sheltering was recommended within 30 km,

The main radionuclides released are the volatile iodine-131, which has a half-life of 8 days and the other main volatile radionuclide caesium-137, which has a much longer half-life (30 years) and may contaminate land for some time. After the major releases (spikes) during the first days, since March 16 the airborne radiation levels had stabilized and steady decreasing.
Estimation of projected *external* doses to population living at different distances from the NPP over one year time period have been performed first by French Institute IRSN and also by US Department of Energy and Japanese Ministry of Education, Culture, Sport, Science and Technology. The results for the most contaminated north-west fallout region show significant values some of them above 200 mSv even outside the 20 km evacuation zone.

The Utility at the Fukushima-1 site is still working hard to bring the situation (cooling and containment functions) under stable control and the Japanese authorities are developing their efforts to deal with the longer term impact on the environment, the people, and the economy.
On April 17 the Tokyo Electric Power Company (Tepco) has published a first roadmap for remediation activities dealing with the disabled Fukushima Daiichi reactors covering the period of time up to the end of the year.

The accident management on Fukushima Daiichi site has been carried out in conditions which have never been considered possible before. The massive disaster which caused the accident has transcended all previous foreseen severe accident scenarios.

Relying on external support, following the accident management instructions, getting the necessary approval for actions not predefined in the accident management (e.g. injection of

seawater), the onsite crisis team and the emergency workers have given their best to understand the status of the plant and take the necessary and possible actions to mitigate and terminate the progression of the severe accident affecting simultaneously 3 reactors and 4 spent fuel pools.
During the evolution of the accident they had to manage the destructive events due to explosions in 4 units which have injured a number of workers.
We express all our sympathy and respect to the operators and workers onsite for their courage, composure and resilience throughout these hard difficulties.

We recognize that we do not have all information and insights of what happened in the affected units, of the progression of the accidents, the operability of systems and equipment and possible interactions between units. This information appears to be not completely available at the moment as the loss of all ac-power, and soon after also of dc-power, has produced a loss of information about the plant status (Control Rooms disabled and in the dark since the loss of dc-power). It is also true that there are questions still unanswered regarding the evolution of the events and the understanding of some phenomena. It will be necessary a certain time to recover all available information and reconstruct the exact evolution of events and its timing.

The Fukushima accident has brought at the attention of utilities, designers and regulators an extremely important set of issues which need to be elaborated.
The accident has shown a clear weakness in the implementation of the defense in depth concept for the seismic event followed by tsunami.

While the NPP structures seem to have successfully withstood the seismic event, the adopted defense against the seism-generated tsunami was not adequate, due to underestimation of the event, incurring in a common-caused loss of ac-power causing, after a partial initial operation of the steam driven reactor cooling system, a loss of cooling function on four units!
These severe conditions have been faced by injecting seawater with temporary mobile equipment and performing other accident management actions in an extremely difficult scenario.

The Fukushima accident shows a peculiar feature: it has highlighted a number of issues and weaknesses that cover a very wide spectrum of technical fields and responsibilities. This means that a lot can be learned from this unique event.
In this sense, one might expect in the future to speak about Fukushima event as a key milestone in the process of evolution of nuclear safety (although the basic safety principles remain unchanged).

At the moment while it is still too early to find full lessons learned from the plant response and the accident management, it is already possible to observe the major facts, the emerging issues and derive first indications, which appear to be very extensive and impacting design, operation and accident management.
It is of the utmost importance to perform detailed analysis of the facts and their causes and learn from them as they can effectively contribute to improve the current and future ''nuclear safety''.

The preliminary considerations and observations elaborated in this report have the aim to contribute to this process. In developing these considerations we do not intend to criticize any involved party as we are aware that things that seem inherently obvious now, certainly weren't so obvious before the accident.

The indications coming from this accident can be referred to ''new design'' and ''operating NPP''.
While for new design it is more comfortable, in terms of time constraints, to feedback the

learning from the Fukushima event, for operating NPP it is a priority to use the Fukushima lessons to undertake a comprehensive risk and safety re-assessment as soon as possible.

Chapter 10 of this report describes in some detail the indications coming from a preliminary analysis of the Fukushima event for ''operating NPPs'' and ''new design'':

a) For NPPs in operation, that will first and promptly benefit from lessons learned in the Fukushima accident, the identified priorities refer to a safety re-assessment of the following topics:
    - Site External Events
    - Multi unit site
    - Spent Fuel Pool
    - H2 Management
    - Total Blackout
    - Loss of Heat Sink
    - Severe Accident Management

   In addition for Operating NPP it is considered of particular relevance to reinforce the scope, the quality and the effectiveness of activities related to Periodic Safety Review (PSR) and Plant Life Extension (PLEX) from the viewpoints of both Operator and Regulator.

b) For new design we know that the current safety conception elaborated for the so called 3rd generation NPP already provides means to deal with a number of shortcomings shown by the Fukushima accident. Nevertheless it is worthwhile to put all indications to the attention of involved parties. The considerations elaborated in this report address the following topics:

    - Siting of NPP and External Events
    - Multi-unit site
    - Seismic Hazard and Tsunami
    - Defense in Depth
    - Spent Fuel Pool
    - Probabilistic Safety Analysis
    - Accident Analysis for External Events
    - Station Blackout
    - Loss of Ultimate Heat Sink
    - H2 Management
    - Accident Management
    - Human Factor
    - Reliability and Habitability of the Emergency Control Center
    - Use of Experience

In conclusion the Fukushima accident contains facts and elements of extreme relevance to be used as learning items and to confirm or improve the current safety level of operating NPPs and of new design.
Industry, operators and regulators are embarking on assessment programs to verify the safety of operating NPPs first and also of NPPs under construction or in the design phase to confirm the safety level, the robustness and resilience to external events in the light of the Fukushima event.
To achieve practical ''lessons learned'' it is necessary to conduct an in-depth analysis of the events and their evolution based on comprehensive data and information and with the support of the combined effort of the international community.

CONTENTS

Fukushima Daiichi NPP site

1. Abbreviations

AA	Accident Analysis
AM	Accident Management
BWR	Boiling Water Reactor
CCF	Common Cause Failure
CR	Control Room
DiD	Defense in Depth
DW	Dry- well
D/G	Diesel Generator
ENSREG	European Nuclear Safety Regulators Group
ECCS	Emergency Core Cooling Systems
ECR	Emergency Control Room
EE	External Event
GE	General Electric
HPCI	High Pressure Cooling Injection
IAEA	International Atomic Energy Agency
IC	Isolation Condenser
ICRP	International Commission on Radiation Protection
IE	Initiating Event
INES	International Nuclear Event Scale
IRSN	Institute for Radiological Protection & Nuclear Safety (France)
JAIF	Japan Atomic Industrial Forum (industry body)
LLSBO	Long Lasting SBO
LOCA	Loss of coolant accident
LPCI	Low Pressure Cooling Injection
MCR	Main Control Room
METI	Ministry of Trade, Economy & Industry (Japan),
MOX	Mixed Oxides
NF	Nuclear Facility
NISA	Nuclear & Industrial Safety Agency (Japan, regulator),
NPP	Nuclear Power Plant
NSC	Nuclear Safety Commission (Japan, policy body)
PCV	Primary containment vessel
PGA	Peak ground acceleration
PLEX	Plant Life Extension
RPV	Reactor Pressure Vessel
RV	Reactor Vessel
RB	Reactor Building
RCIC	Reactor Core Isolation Cooling
SA	Severe Accident
SAMG	Severe Accident Management Guidelines
SBO	Station Blackout
SFP	Spent Fuel Pool
SSC	Structures Systems and Components
TB	Turbine Building
Tepco	Tokyo Electric Power Company
TSC	Technical Support Centre
WENRA	Western Europe Nuclear Regulators Association
WW	Wet-well

Fukushima Daiichi Nuclear Accident
Preliminary Report

2. Introduction

This report has been prepared with the aim to provide background information about the Fukushima 1 NPP and report on the main aspects of the accident: the initiator seismic event and consequent tsunami, the evolution of the accident, its management and the radiological impact.
A number of preliminary considerations are elaborated to contribute to the process to learn from the Fukushima accident.

3. Background

There are two close nuclear sites on the west coast of Japan, distant 11 km, named Fukushima Daiichi (first) and Fukushima Daiini (second).
Fukushima Daichii NPP consists of six BWR (Boiling Water Reactor) units with power ranging from 460 to 1100 MWe with a total net capacity of 4.7 GW.

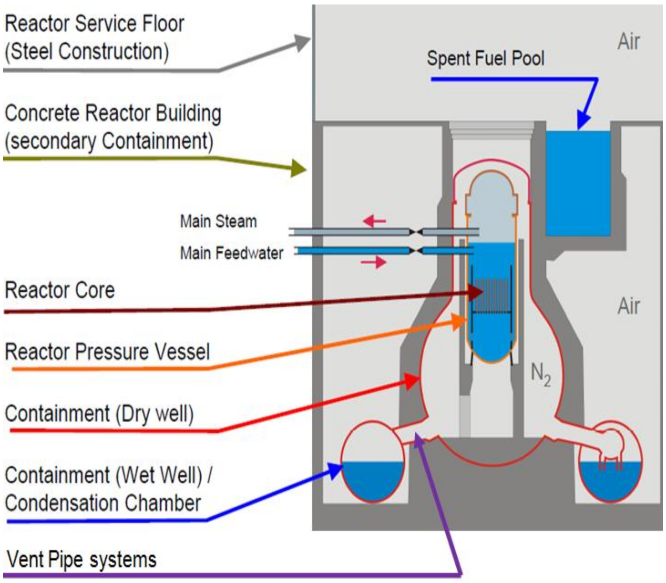
Fukushima Daiichi					
Unit	*Model*	*MWe*	*Nuclear Supply*	*Operation*	*Status 11.03.11*
Unit 1	BWR3 MARK-I	460	GE	1971	operating
Unit 2	BWR4 MARK-I	784	GE	1974	operating
Unit 3	BWR4 MARK-I	784	Toshiba (licen. GE)	1976	operating
Unit 4	BWR4 MARK-I	784	Hitachi (licen. GE)	1978	outage[1]
Unit 5	BWR4 MARK-I	784	Toshiba (licen. GE)	1978	outage
Unit 6	BWR5 MARK-II	1100	GE	1979	outage

The Fukushima Daiini NPP consists of 4 BWR5 MARK-II units, 1100 MWe each. Nuclear supply Toshiba, commercial operation since 1982, 1984, 1985, 1987 . All of them were in operation on March 11, 2011.

[1] Reactor vessel empty for inspection: core discharged in the spent fuel pool

Fukushima Daiichi Design Conception

Primary coolant circuit - The main feature of boiling water reactors (BWR), originally developed by General Electric (USA) since the '50s, is to have two-phase flow conditions (water + steam) at the top of core. In these reactors, therefore, there is only one circuit (primary) and it is not present a secondary circuit for the steam production, as it is the case of pressurized water reactors type (PWR). The steam produced in the reactor core is delivered to the turbine located in an adjacent building. After driving the turbines it is condensed and the water is returned from the condenser to the pressure vessel.



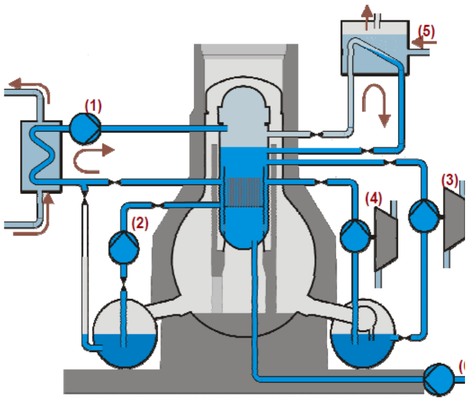
Two recirculation jet-pumps provide for forcing water down around the reactor core and shroud. When the reactor is shut down, the steam in the main circuit is diverted via a bypass line directly to the condensers, and the heat is dumped there, to the sea.

Residual heat removal - In shutdown mode, the Residual Heat Removal (RHR) system (connected to the two jet-pump recirculation circuits), driven by smaller electric pumps, circulates water from the reactor pressure vessel to RHR heat exchangers which dump the heat to the sea.

Reactor Core Isolation Cooling (RCIC) - A Reactor Core Isolation Cooling (RCIC) is envisaged to cool the reactor when it is isolated, closure of main stream isolation valves, from the turbine. It is actuated automatically and can provide make-up water to the reactor vessel (without any heat removal circuit). It is driven by a small steam turbine using steam from decay heat, injecting water from a condensate storage tank or the suppression pool and controlled by the DC battery system.

The RCIC systems are available in all units except the oldest unit 1 where the same function is played by the Isolation Condenser.

The RCIC in unit 2 and 3 and the IC in unit 1 played a helpful role in the first part of the Fukushima accident as far as: DC was available, water was available in the IC and T in the suppression pool was low enough to allow the operation of the RCIC.



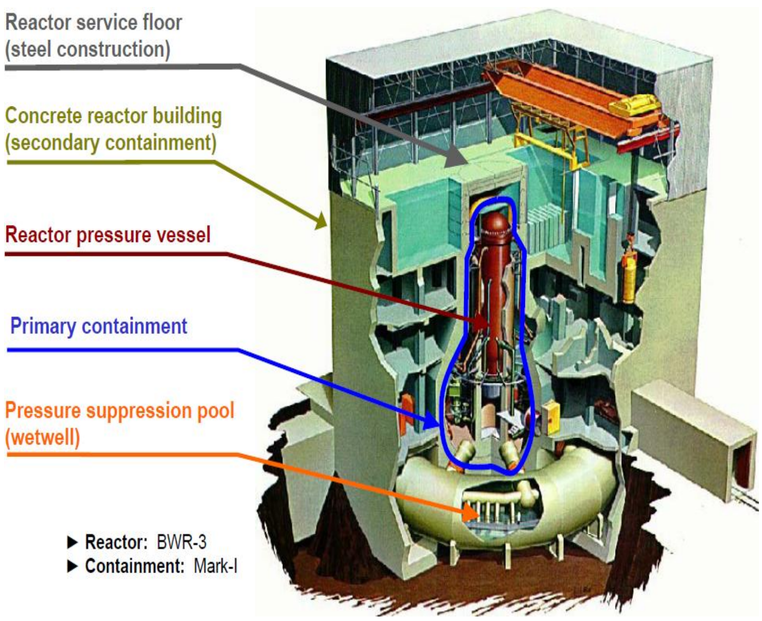
The Emergency Core Cooling Systems are composed of:

1) Residual Heat Removal System
2) Low-Pressure Core Spray (for LOCA)
3) High-Pressure Core Injection (for LOCA)
4) Reactor Core Isolation cooling (UNIT 2,3 [BWR4])

Emergency Core Cooling System (ECCS)- The Emergency Core Cooling System (ECCS) is made of a high-pressure

and low-pressure subsystems. The high pressure coolant injection (HPCI) system has pumps powered by steam turbines which are designed to work over a wide pressure range.
The HPCI draws water from the large torus suppression chamber beneath the reactor as well as a water storage tank. Under about 700 kPa, the Low-Pressure Coolant Injection (LPCI) is available which injects water through the RHR system but utilizing suppression pool water, and a core spray system, all electrically-driven. All ECCS sub-systems require electrical power to operate.
Beyond these original systems, it seems that Tepco in 1990s installed provision for water injection via the fire extinguisher system through the RHR system (injecting in the Vessel via the jet-pump nozzles) as part of it Severe Accident Management (SAM) countermeasures.

Containment System – The containment system of the BWR Mark is made of a free-standing bulb-shaped **drywell** (DW) (30 mm steel thick) which is backed by a reinforced concrete shell, and connected to a torus-shaped **wetwel**l (WW) in the lower part of the reactor building containing the suppression pool. The design pressure is the same for DW and WW.
The DW, also known as the Primary Containment Vessel (PCV), contains the reactor pressure vessel (RPV). The water in the suppression pool acts as an energy-absorbing medium in the initial phase of a loss of coolant accident, after it needs to be cooled.
The WW is connected to the DW by a system of downcomer vent lines, which discharge under the suppression pool water in the event of high pressure in the DW.
The function of the containment system is to contain the energy released during a postulated design-basis loss-of-coolant accident (LOCA of any size) and to protect the reactor from external events. The design-basis break is the largest reactor recirculation system pipe break. The primary containment system is designed to withstand the combined seismic, pressure and temperature loads for this event and maintain integrity. The containment system accommodates this accident without exceeding the design leakage rate.



The primary containment is one of the three main barriers limiting release of fission products from the BWR nuclear fuel into the environment. Other barriers include the fuel rod cladding and the reactor pressure vessel together with its piping, which form the reactor coolant pressure boundary.
In addition to the three fission product barriers, the secondary containment surrounds the primary and is not designed to perform containment function.

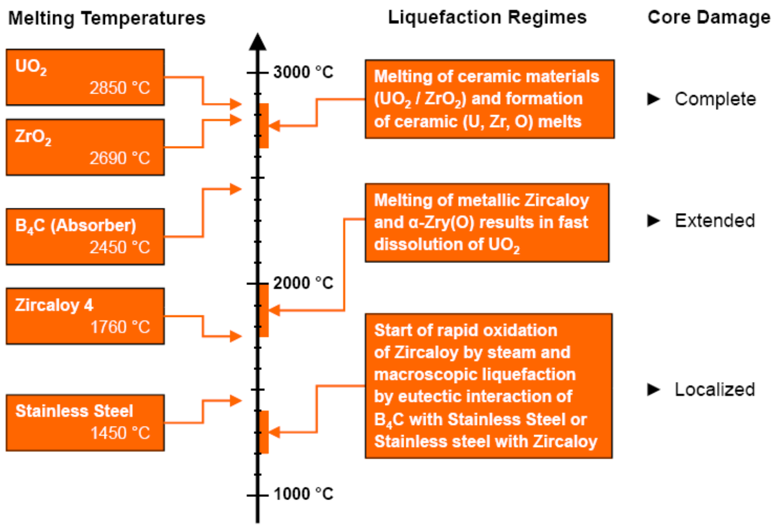
During normal operation, the DW atmosphere and the WW atmosphere are filled with inert nitrogen, and the water in the suppression pool of the WW is at ambient temperature

If a loss of coolant accident (LOCA) occurs, steam flows from the DW through a set of vent lines and pipes into the suppression pool, where the steam is condensed.
Steam can also be released from the reactor vessel through the safety relief valves and associated piping directly into the suppression pool.
Steam will be condensed in the WW, but hydrogen and noble gases are not condensable and will pressurize the system, the same will happen with steam if the WW water is boiling. In this case emergency systems will activate to cool the WW water.

Containment depressurization - Overpressure in the primary containment (above 300 kPa) can be vented through the 120 m emission stack via a hardened pipe or into the secondary containment above the reactor service floor of the building.

Secondary Containment - The secondary containment is made of the part of the reactor building external to the primary containment. It houses the emergency core cooling systems, other auxiliary systems, routing of piping and cables and , in the upper part adjacent to the service floor, the spent/ used fuel pool. It is not designed to contain high pressure.

Conditions for fuel meltdown – The meltdown of the fuel contained in the fuel rods would start to occur if the fuel itself reaches temperature up to 2800°C. If there is fuel meltdown the fuel rods slump within the assemblies. The “corium” (a mixture of molten cladding, fuel, and structural steel) drops to the bottom and can attack the reactor vessel steel material whose melting point is about 1500°C. This means that there is an obvious possibility that the corium can penetrate the steel if it remains hot enough. (in the 1979 US Three Mile Island accident, it didn't, though about half the core melted and it went 15 mm into the 225 mm thick pressure vessel steel).
But the whole fuel melt scenario is much more probable when the severe sequence with loss of coolant function starts when the reactor is at full power than in the Fukushima situation (where it has started beyond the first few hours). Before fuel melting, cladding cracks at about 1200°C, its oxidation begins at about 1300°C (releasing hydrogen) and the zirconium cladding melts at about 1850°C. These temperatures can be reached also in some days after shutdown in the absence of cooling.



Spent Fuel Pool - The spent fuel from the reactor core at the end of its core cycle is stored in spent fuel pools located near the top of each reactor so that the fuel can be unloaded under wate.When the drywell is open, the reactor pressure vessel is open and flooded. The spent fuel from the ponds is later transferred to the site central used/spent fuel storage. The ponds can contain also some fresh fuel.

Unit 2, 3 & 4 ponds are about 12 x 10 meters and some less for unit 1 . The temperature of these ponds is normally low, around 30°C when the recirculation and cooling system is working. They are designed to be safe at about 85°C in the absence of forced recirculation and with moderate fuel load. They are about 12 meters deep, so the fuel is normally covered by 7 meters of water. At the time of accident there was no MOX fuel present in any of the ponds and the situation of stored fuel in each SFP of units 1-4 is shown below:

Spent Fuel Pool	**Unit 1**	**Unit 2**	**Unit 3**	**Unit 4**
Dimension	12x7x12	12x10x12	12x10x12	12x10x12
Nominal capacity	900	1240	1220	1590
Spent fuel loaded assemblies	292	587	514	1331 (783 + discharged core of 548),
New fuel loaded assemblies	100	28	52	204

The central fuel storage on site near unit 4 has a pond about 12 x 29 meters, 11 m deep, with capacity of 3828 m^3 and able to hold 6840 fuel assemblies. At time of the accident 6375 assemblies were stored in the undamaged central pool storage on site, with very low decay heat, and 408 in dry cask storage, utilized since 1995 for used fuel no longer needing much cooling.

Siting and layout - All six units are built at a level of 10 meters over the seal level. Each unit is equipped with 2 redundant D/G and the units 6 has one more D/G air-cooled while all others are seawater-cooled. The Turbine Buildings, parallel to the shore line, are located on the west side of the Reactor Buildings (RBs) at a distance from the sea around 150 m. The first four RBs are on the same line and apparently not so distant from each other. The units 5 and 6 form a second group relatively distant from the others.
The sea water is the main heat sink not only for the turbine condensers but also for the residual heat removal (RHR) systems and for the emergency D/Gs (except one air cooled). The D/Gs are located under the ground floor of the turbine buildings, and much of the reactors switchgear are on the ground floor in the turbine buildings.
The units 1 to 4 are connected to a 275 kV electric grid and the units 5-6 to a 500 kV electric grids.

Seismic Design - Japanese nuclear power plants are designed to withstand specified earthquake intensities. If a pre-set level of ground acceleration is reached, systems will be activated to automatically shutdown the reactor. In this case the set scram level was 135 Gal at Daiichi (150 Gal at Daini).
The design basis ground motion for both Fukushima plants had been upgraded since 2006, and are quoted at horizontal 438-489 Gal for Daiichi and 415-434 Gal for Daiini. At this level of ground motion the units must retain their safety functions.

The recorded data of the earthquake of 11 March show that 550 Gal (0.56 g) was the maximum ground acceleration for Daiichi, in the foundation of unit 2 , and 254 Gal was maximum for Daiini. Daiichi units 2, 3 and 5 exceeded their maximum response acceleration design basis in E-W direction by about 20%. Recording was over 130-150 seconds.

Various parameters have been proposed in the literature for estimation of the destructive power of an earthquake. Among these parameters, the CAV (cumulative absolute velocity) has been recently proposed. Using the data recorded in the Tohoku event, the CAV can be evaluated in 10, whereas in Kashiwazaki-Kariva earthquake of 2007 the CAV was equal to 2 with a recorded Peak Ground Acceleration (PGA) much higher that in Fukushima. This is apparently due to the exceptional duration of the Tohoku event.

Tsunami Design - The design basis tsunami height was 5.7 m for Daiichi and 5.2 m for Daini, though the Daiichi plant was built about 10 meters above sea level and Daiini 13 meters above. Tsunami height coming ashore was more than 14 meters at Fukushima Daiichi (apparently much less at Daini site distant 11 km) and the turbine halls were under some 5 meters of seawater until the levels lowered.
The flooding entered also the trenches and through them the basement of connected buildings.

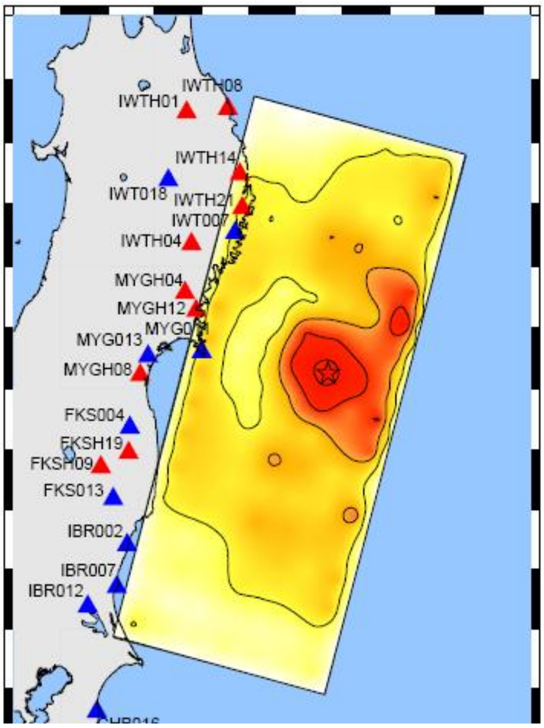
The maximum slip on the source fault of the tsunami was 23 meters, at about 160 km from Fukushima. In the last century there have been eight tsunamis in the region with maximum amplitudes at the source over 10 meters (some much more), originated by earthquakes of magnitude 7.7 to 8.4, on average one every 12 years.
Those in 1983 and in 1993 were the most recent affecting Japan, with maximum heights at origin of 14.5 meters and 31 meters respectively, both induced by magnitude 7.7 earthquakes.

A Japanese government's Earthquake Research Committee has elaborated a report on earthquakes and tsunamis off the Pacific coastline of northeastern Japan which was going to be released in April 2011. The document includes the analysis of a magnitude 8.3 earthquake that struck the region more than 1140 years ago. This was apparently caused when 3 sections of the seabed shifted simultaneously, triggering enormous tsunamis that flooded vast areas of Miyagi and Fukushima prefectures. The report concludes that the region should be alerted of the risk of a similar disaster striking again.

4. Tohoku earthquake and generated tsunami

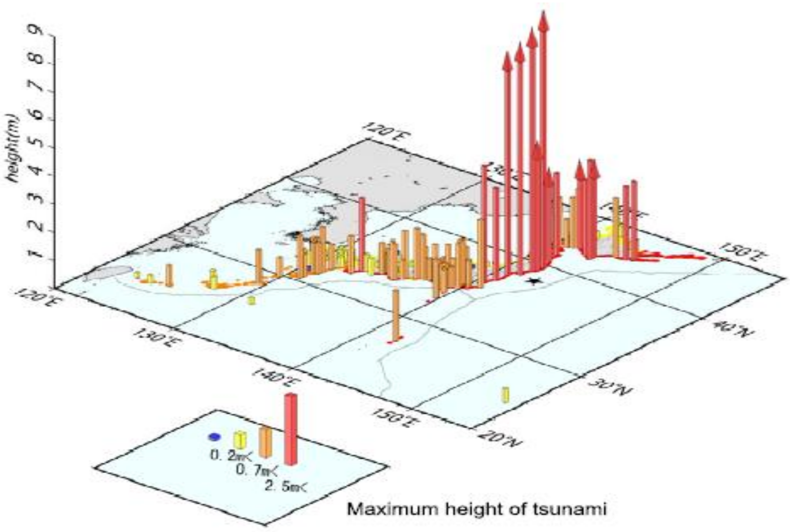
On March 11th (05:46 UTC), 2011 a big earthquake (M_w=9.0, depth 24 km) stroke the Pacific coast of Japan and produced a giant tsunami which killed almost 30 thousand people. The earthquake, one of the five ever recorded greatest earthquakes in the world, was caused by the subduction of the Pacific slab beneath the North American plate; the rupture plane was about 500 km long and 200 km wide and the largest slip was around 23m, for a released moment magnitude of about 3.0×10^{23} Nm.

The earthquake focus was located 150 km off-shore the Miyagi prefecture in the Honshu Island at a depth of 24 km. The figure aside shows the fault plane model (ref. /11/) along with the slip distribution on the fault, the epicentre (red arrow) and some of the recording stations along the Honshu Pacific coast (triangles).



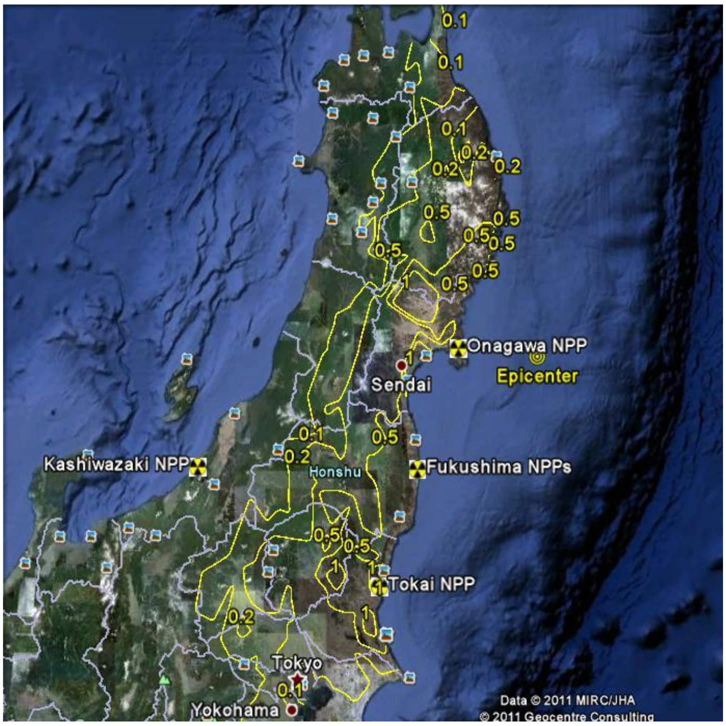
In less than half an hour the earthquake was followed by a massive tsunami which locally reached a run-up height as high as 20 meters (ref. /16/) that travelled in the order of 10 km inland. Inundation depths at Fukushima-Daiichi and Daini were 14 and 7 meters, respectively. The figure below (ref. /12/) shows the wave heights of tsunami along the coast.

The difference in the sea wave heights is mainly due to the largest slip along the fault plane just in front of the Hoshika Peninsula (east of Sendai) which can be observed in the figure above, besides differences in the local bathymetry, of course.

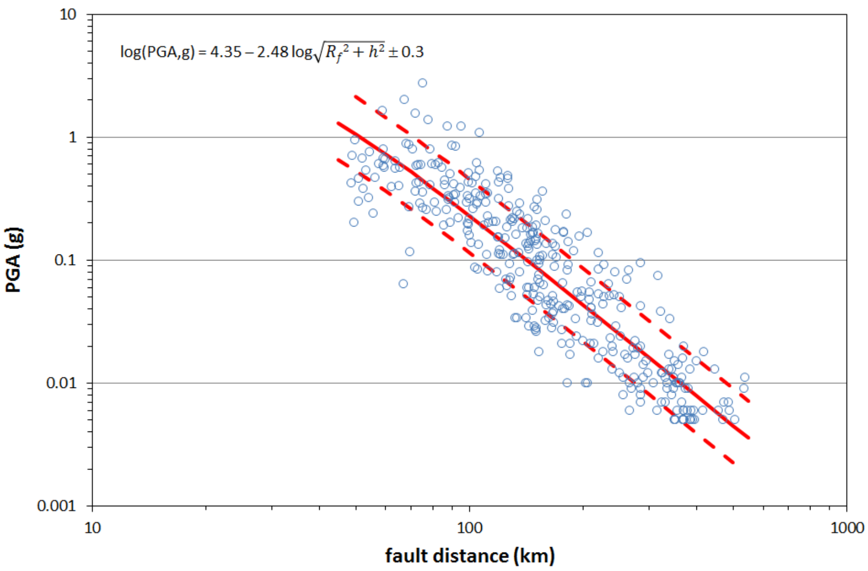


Beyond the destruction of houses, bridges, harbours and infrastructures, the earthquake and tsunami severely threatened three nuclear installations, one of which suffered very severe damages and the release of radioactive material. Hereinafter the ground motion recorded during the earthquake is synthetically reviewed with a special emphasis to its role in the response of the nuclear power plants threatened by the earthquake.

Strong ground motions showed a significant duration (between 120 and 170 seconds), a very high destructiveness potential (CAV-values of some g's-sec, when a threshold damaging value is set at only 0.16 g-sec) and Arias intensity values of some meters per second. Nevertheless the recorded peak ground accelerations (PGA) were not extremely high as one could expect from such a huge earthquake. Only few records reported PGAs as high as 1.0 g, while the spatial distribution of PGA-values show that the coast was affected by PGA-values around 0.5 g on average (figure aside where the contour lines are PGA-values).

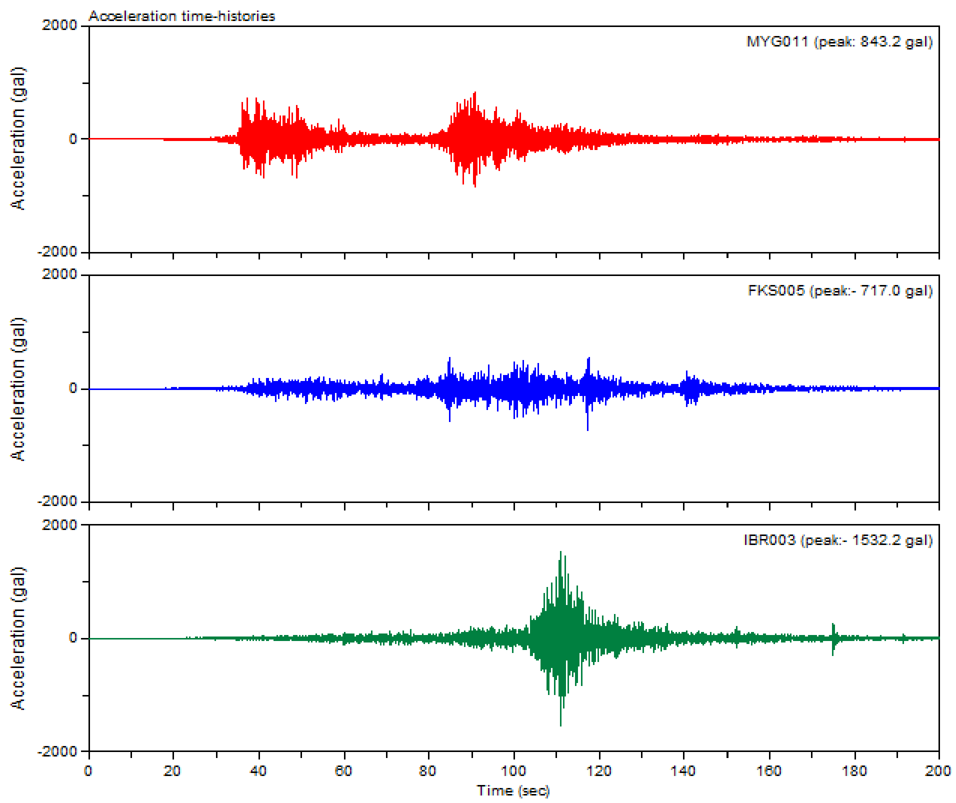


The restrained PGA-values were mainly due to the very low frequency content of the source radiation and travel path which are reflected in the Fourier spectra of the records. Moreover, they did attenuate rapidly with distance from the causative fault as shown in the figure below, where the red lines display the median and variance of PGA as a function of fault distance for the main shock.

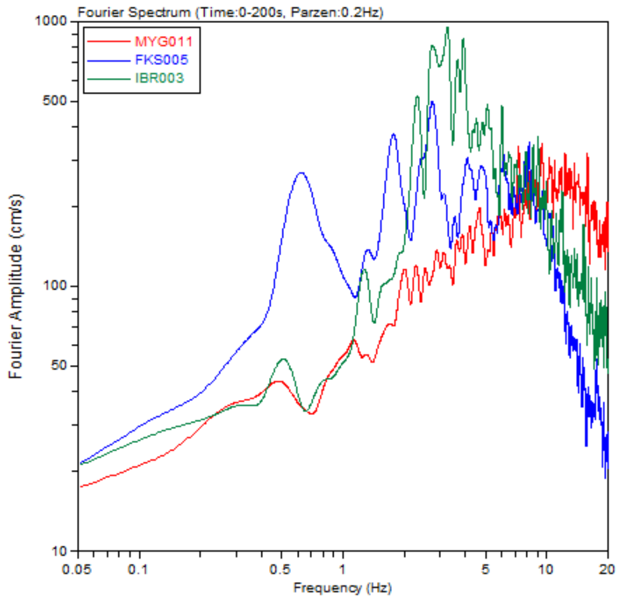


The records of the nuclear installations most severely shaken by the Honshu earthquake are still unavailable, thus the closest records to NPPs have been extracted from the KiNet database (www.k-net.bosai.go.jp) to infer the probable shaking suffered by Onagawa, Fukushima (Daiichi and Daini as well) and Tokai NPPs, located from north to south, respectively, along the coast most severely shaken.
The records selected to represent the most feasible shaking experienced by the NPPs are MYG011, 11 km away from Onagawa NPP, FKS005, 16 km away from Fukushima NPP, and IBR003, 14 km away from Tokai NPP. The ground motion values recorded by the seismic stations in free-field conditions are reported in the table below along with the design values of the NPPs. The figures below show the recorded time-histories and spectra from which the following comments arise:

1. The waveforms show a very complex pattern of the fault rupture, with several and different slip areas from north to south: northward (MYG011) two main and very distinct seismic phases corresponding to as many wide slip areas are clearly visible, which southward reduces to one alone (IBR003) due to the disappearance of the first phase; in the middle both but less distinct phases are still visible with the second one becoming predominant. IBR003 experienced the largest PGA, exceeding 1g, while FKS005 experienced the smallest one but anyway exceeding 0.7g; peak velocities and displacements exceeded 50 cm/s and 10 cm, respectively. Damage-related ground motion parameters were always very high, with Arias intensity values exceeding 20 m/s and cumulative absolute velocities around 9 g*sec, making this shaking one of the strongest ever recorded.



2. MYG011 and FKS005 show a spectral content extending over a large frequency range (between 0.5 and 10 Hz), with the latter exceeding the former in absolute values. IBR003 reaches the highest spectral values but in a narrower spectral range, around 2-3 Hz.

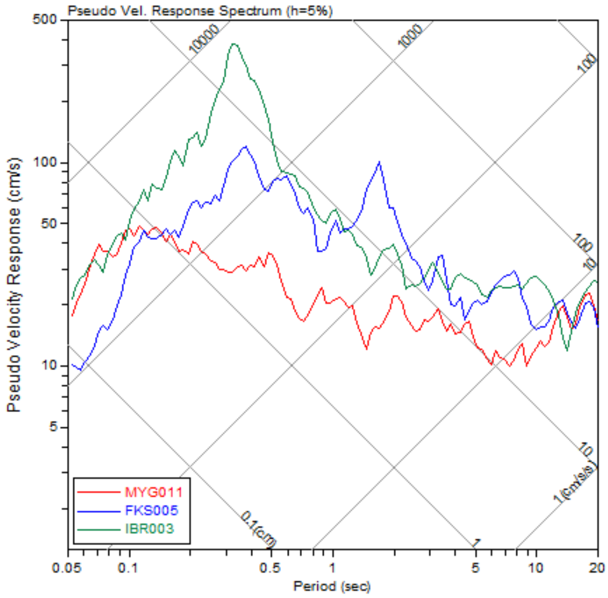


Values of PGA recorded at Fukushima Daiichi and Daini nuclear power stations are reported in the following table (from Tepco on date 2011, April 1st):

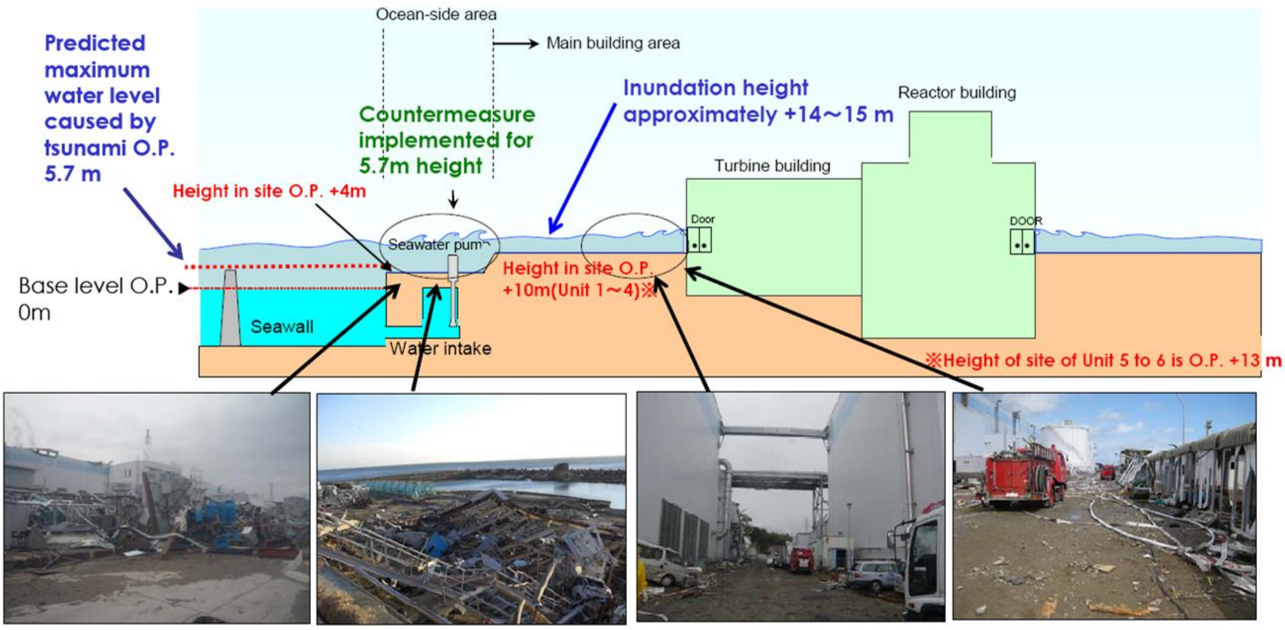
Observation Point (The lowest basement of reactor buildings)		Observed data (interim※1) Maximum Response Acceleration (gal)			Maximum Response Acceleration against Basic Earthquake Ground Motion (gal)		
		Horizontal (N-S)	Horizontal (E-W)	Vertical	Horizontal (N-S)	Horizontal (E-W)	Vertical
Fukushima Daiichi	Unit 1	460※2	447※2	258※2	487	489	412
	Unit 2	348※2	550※2	302※2	441	438	420
	Unit 3	322※2	507※2	231※2	449	441	429
	Unit 4	281※2	319※2	200※2	447	445	422
	Unit 5	311※2	548※2	256※2	452	452	427
	Unit 6	298※2	444※2	244	445	448	415
Fukushima Daini	Unit 1	254	230※2	305	434	434	512
	Unit 2	243	196※2	232※2	428	429	504
	Unit 3	277※2	216※2	208※2	428	430	504
	Unit 4	210※2	205※2	288※2	415	415	504

※1: The data above is interim and can be changed. ※2: The recording time was about 130-150 seconds.

One can infer as observed PGA-values at Fukushima-Daiichi were globally in the same order of the design values; at unit 2 the recorded accelerations exceeded the design values by a 25% on average, a difference which is commonly accommodated by the usual safety margins adopted in the nuclear design. At Fukushima-Daini (only 10 km apart) the observed PGA-values were even lower than the design ones by about twice. Since threshold accelerations for reactor scram were set between 135 and 150 gal, it's easy to infer that scram was successfully operated at both nuclear stations., and that the accident at Fukushima-Daiichi was due to the failures induced by the tsunami that followed the shaking.



In this regard the figure below (from Tepco on date 2011, April 9th) shows the survey of the tsunami effects at Fukushima-Daiichi:



The design tsunami height was about 6 meters above the sea level while the tsunami following the earthquake was around 14-15 meters high; the resulting inundation depth was around 4-5 meters in most of the main building and ocean-side areas, including the outdoor seawater pumps.

Prior the current earthquake, the seismic hazard of the Miyagi off-shore area was based on an anticipated earthquake of magnitude 7.5 or greater with an average return period of 30 years, and on an anticipated shaking in the Sendai area around 0.3-0.4g with a 10% probability of exceedance in 50 years (corresponding to a return period around 500 years). By extrapolation, a magnitude 9 or greater would therefore have an average return period around 1,000 years.

The last expected earthquake in the area occurred on 1978, June 12th with a M_w=7.4 which killed some tens of people and triggered a small tsunami, less than 1 meter in height. Recent studies highlighted at least three giant tsunami occurred in the Miyagi prefecture in the last 3 thousand years, the last one occurred in 869 A.D., whose run-up was estimated to have travelled 4-5 km inland, based on the identification of tsunami sediments (sand deposits).
The same study (Satake et al. 2007[2]) assessed that a similar earthquake with a moment magnitude between 8.1 and 8.3, had a 99% probability to occur in the next 30 years (!).

Despite the expected seismic shakings at the NPP stations were estimated for a lower magnitude earthquake (around M_w=8 based on the Si and Midorikawa, 1999[3] attenuation relationship), the observed accelerations didn't significantly exceed the design ones, thus only minor direct damages due to the seismic shaking may have probably been induced.

In conclusion, only on the basis of the observed peak ground accelerations, one may suppose that the seismic shaking could have been not so much relevant in causing the onsite severe accident conditions, even if a deeper analysis of the relationships between accelerations and response will be possible only once both time-history records and damage surveys of the complete SSCs will be available. The impression is that the tsunami played the major role in causing the accident.

[2] Tsunami source of the unusual AD 869 earthquake off Miyagi, Japan, inferred from tsunami deposits and numerical simulation of inundation. *American Geophysical Union, Fall Meeting 2007, abstract #T31G-03*
[3] Attenuation Relations for Peak Ground Acceleration and Velocity Considering Effects of Fault Type and Site condition.*Journal of Structural Construction Engineering, No. 523, 63-70*

5. Timeline of events and discussion

The **Tohoku earthquake** with magnitude 9.0 stroke the east coast of Japan at 14.46 on Friday 11 March and the generated tsunami hit the coast around 20-30 minutes late.
The earthquake, centered 130 km offshore the city of Sendai in Miyagi prefecture on the eastern cost of Honshu Island (the main part of Japan), was a rare and complex double quake giving a severe duration of about 3 minutes. Japan moved a few meters east and the local coastline subsided half a meter.

Eleven reactors at four nuclear power plants in the region were operating at the time (Tepco's Fukushima Daiichi 1, 2, 3 and Fukushima Daini 1, 2, 3, 4, Tohoku's Onagawa 1, 2, 3, and Japco's Tokai Daini, total 9377 MWe and all shut down automatically when the quake hit.

In the table below are reported the timeline of main events for the site of Fukushima Daiichi NPP together with some consideration and open issues.
The source of information are the published reports since the start of the accident by Tepco, NISA, JAIF and other international organization (IAEA, WNA, WNN, IRSN, GRS, others).
Other information have been achieved by interview with Japanese experts from NISA and JNES.

We recognize that we do not have all detailed information regarding what happened in the affected units, the progression of the accidents, the status of operability of systems and equipment, the interactions between units. This information is probably not completely available at the moment as the loss of all ac-power and soon after also of dc-power has produced a blackout in the availability of information about plant status (e.g loss of power to the Control Room). It will be necessary a certain time to recover this information, resolve all open questions and reconstruct the exact evolution of events and its timing. We also do not have clear view of the basis for operator decisions during the accident management and the way some actions were implemented.

MAIN EVENTS

March 11 14:46	**Tohoku earthquake hits Fukushima Daiichi NPP** The units 1, 2 and 3 which were in operation at Fukushima Daiichi and shut down automatically when the quake hit the site. From the available reports it results that the external ac-power was lost due to the seism. Power from backup generators (automatically started) was available to actuate the main steam dump and feed the Reactor Heat Removal (RHR) system cooling pumps and also to ensure the cooling of the Spent Fuel Pool. It appears that the Structures, Systems and Components (SSCs) of the units withstood successfully to the earthquake keeping their functionality. Possible damages to structures and equipment induced by the seism should be identified by detailed analysis and walk down.
March 11 15:41	**Station blackout due to the tsunami hitting Fukushima-Daiichi NPP**

	At 15.42 there was a total blackout due to loss of all D/Gs induced by the damages produced by the tsunami. The exact time interval between the arrival of the tsunami and the loss of each D/G, the failure mode of the D/Gs and differences need to be investigated. We know that the tsunami destroyed the sea water intakes to the NPP and overwhelmed the plants' physical structures, causing inundation, wetting of many components, making many areas inaccessible during the inundation and thus making further operations impossible during that time. The internal flooding of the lower parts of the building on the site appears to happened also through the connecting underground trenches which were exposed to tsunami wave (see the cause of the death, happened on March 11 soon after the tsunami and discovered on March 30, of two workers in the basement of turbine of unit 4). The resulting accident event was a '' **total station blackout''** for units 1, 2, 3 and 4: in fact 12 of 13 back-up diesel generators (D/G) on site, located in the basements of the turbine buildings, were disabled. The electrical switchgears underground or at ground floor were also disabled. The cooling functions of the reactors in unit 1, 2 and 3 were practically lost (a part some initial cooling by steam driven systems), the cooling functions of the spent fuel pool in units 1, 2, 3 and 4 were lost, and so the ultimate heat sink. It of interest to investigate in which extent the loss of all D/G has been due to a) the damages made by the tsunami to the coiling water intakes and pumps and to b) the flooding of the ground level of the site damaging the encountered equipment and infiltrating the buildings. In this respect the analysis of what has been experienced in Fukushima Daini can be useful as the tsunami hitting Daini was about seven meters high, overcoming the barrier of 5.2 meters but not inundating, as far as we know, the ground level of the site. One hour after shutdown the reactors were still producing about 1.5% of their nominal thermal power due fission product decay (22 MW in unit 1 and 33 MW in units 2 & 3). Without heat removal from the core, the produced steam in the RV is discharged trough safety valves and condensed in the suppression pool (WW) under the reactor, with the consequential quite rapidly increase of temperature and pressure in the reactor containment. The availability of dc-power initially after the tsunami has allowed the operation of Isolation Condenser in unit 1 and of RCIC in unit 2 and 3 for different duration. It seems that in unit 3 there was a contribution to the initial cooling function also from the turbo driven HPCI (high pressure coolant injection). There are no verified information on how long the dc power was available in the affected units 1, 2 ,3 and 4. Consequently we also do not have information about the time in which the control rooms of each unit were no more operative due to loss of dc-power. Moreover due to loss of electrical supply the control rooms remained in the dark.

	It comes the question of how were got the information about the plant status during the accident management to monitor, make decisions and implement actions. From BWR design conception the lack of dc power causes the loss of cooling functions ensured by steam driven systems like IC or RCIC or HPCI as the motor operated valves on the connecting lines with the primary circuit are designed to fail close in case of loss of power. In the units 5 and 6, overcoming some difficulties and performing some alignments, the operator was able to ensure the RHR function for the reactor core and for the Spent Fuel Pool due to the operability of the 13^{th} D/G air cooled.
March 11 16.36	**Isolation condenser stops in unit 1.** The reason was maybe due to loss of dc-power (closure of valves) or to evaporation of all water in the isolation condenser pool. From this moment in unit 1 water levels in the RV dropped dramatically with consequent continuous increase of the fuel T. At the same time the pressure inside the primary containment (PCV) started to increase steadily leading to the need of depressurization to the atmosphere.
March 11 19.03	**Declaration of nuclear emergency** The nuclear emergency was declared, at 8.50pm the Fukushima Prefecture issued an evacuation order for people within 2 km of the plant. At 9.23 pm the Prime Minister extended this to 3 km, and at 5.44 am on March 12 he extended it to 10 km. He visited the plant soon after. At 6.25 pm on Saturday 12th he extended the evacuation zone to 20 km and sheltering up to 30 km. On March 25 it was proposed a voluntary evacuation between 20 and 30 km. . The initial rating for the accident on the International Nuclear and Radiological Event Scale (INES) of the IAEA was **level 4**.
March 12 10.17 (or 14.30)	**Venting of the containment of unit 1** Over the first twelve hours pressure inside the primary containment of unit 1 increased steadily and led to venting from the DW when the pressure reached twice the design level (over 750 kPag compared with ''maximum'' 430 kPag). The available information indicates that the vent was taking place trough the service floor at the top of the reactor building. It is not clarified yet why the vent did not take place via the stack (120 m) if it was a decision of the operator or it was due to damage to the piping connection to the stack by the tsunami. We have no confirmation of how has been actuated the venting, probably by local operator action.
March 12 15.36	**H2 explosion on service floor of unit 1** The hydrogen explosion took place on the service floor in the reactor building of

	unit 1 above the reactor containment, blowing off much of the roof and cladding on the top part of the reactor building. The H2 was accumulating due to the venting from the PCV but most probably also to diffusion of H2 trough the damaged seals of the PCV exposed to high T and high P. It is not clarified if H2 recombiners were installed on the Fukushima NPP units and, if yes, what kind of recombiners and where.
March 12 20.20	**Seawater injection to unit 1** Apparently after 27 hours with no injection of water into the reactor vessel (RV) of unit 1, the injection of sea water was started. The injection has been realized with mobile pumps, via the fire extinguishing system connected with make-up system lines (or the RHR system). The injection of seawater appears to have required a long time to be implemented. It important to analyze the procedural and operating difficulty encountered. This delay in the initial part of the evolution determines the evolvement towards severe conditions with all known consequences. On March 25 it was possible to replace the seawater by fresh water from a nearby dam.
March 13 11.30	**Venting of the containment of unit 2** Pressure in the primary containment of unit 2 was vented on March 13 and again on March 15. There are information saying that blowout panels near the top of the reactor building were also opened. We have no confirmation that this was the reason why there has been no H2 explosion on the service floor in unit 2.
March 13 05.10	**Isolation pump stops in unit 3** After failure of the injection of water to the RV (stop of RCIC and of HPCI which was apparently working on unit 3)) water levels dropped dramatically.
March 13 08.41	**Venting of the containment of unit 3** Venting of the PCV of unit 3 took place. It was repeated at subsequent intervals. No clear information is available about the way the venting has been actuated probably by local operator action.
March 13 13.12	**Seawater injection to unit 3** After 7 hours with no injection of water into the RV of unit 3, the injection of sea water was started. Apparently this injection took place, with mobile pumps, via the fire extinguishing system connected into the RHR system. On March 25 it was possible to replace the seawater by fresh water from a nearby dam.

Mach 13	**Seawater injection in the primary containment of unit 1** The operator decided to inject seawater in the Primary Containment flooding the RPV up to the level of the top of the reactor core. The basis of decision are not available. Later Tepco assured NISA that the structural integrity was not challenged due to the flooding.
March 14 04.08	**High water temperature in SFP of unit4** The temperature of the water in the SFP increased up to 84°C
March 14 11.01	**H2 explosion on service floor of unit 3** On Monday 14th at 5.20 am the venting from unit 3 was repeated to the service floor of unit 3, though both RPV and drywell pressure remained at about 500 kPag. At 11.01 am a very large hydrogen explosion on the service floor in the reactor building of unit 3 above the reactor containment happened destroying the roof and the walls of the top part of the building. This explosion, which mobilized a lot of debris was probably due to accumulation of H2 in the volume over the service floor.
March 14 13.25	**Isolation pump stops in unit 2** Apparently the steam-driven Reactor Core Isolation Cooling (RCIC) system in unit 2 functioned until midday of March 14. It is not clear how it was ensured such long operating period of time. The reactor water level dropped rapidly after RCIC cooling was lost.
March 14 16.34	**Seawater injection to unit 2** Seawater injection to unit 2 reactor vessel was started via the fire-fighting line. However, RPV pressure was very high from mid of March 14th and drywell pressure reached 650 kPag, well above design base maximum of 380 kPag. On March 25 it was possible to replace the seawater by fresh water from a nearby dam.
March 15 06.00	**Hydrogen explosion at Spent Fuel Pool of unit 4** An explosion took place in the top part of the building, near the fuel pond, which destroyed the top of the building and further damaged unit 3's upper structure. Probably due to H2 produced by oxidation of uncovered fuel cladding in the pool. Some leakage of water from the pool could have been caused by the earthquake. It appears that the water level dropped due to evaporation, or boiling, caused by the high heat load (3 MW) from 1331 fuel assemblies once the cooling system stopped working.

March 15 06.14	**Explosion in the PCV of unit 2** An explosion took place in the primary containment of unit 2, this has apparently ruptured its pressure suppression chamber under the actual reactor, releasing significant radioactivity and dropping the drywell pressure inside. The cause of the explosion needs to be investigated. The unit 2 is the one which received longer cooling function after the SBO due to RCIC. It is apparently noted that soon after the loss of this function a fast progression of the accident led to an explosion inside the primary containment. We have information that venting of the containment in unit 2 was performed on March 13 (11.30) and on March 15. Containment damage is suspected. Since about March 17 the pressure in the RPV has been atmospheric, and drywell pressure about 200 kPa (100 above atmospheric). On April 1st a crack was discovered in the wall of a 2m deep services pit which was leaking highly-contaminated water to the sea, apparently from the reactor itself. Tepco plugged it early on 6 April after some radioactivity had been released.
March 15 09.40	**Fire in the SFP of unit 4** The fire was seen a few hours after the explosion on the top of the reactor building of unit 4. Soon after the radiation level near the building reached 400 mSv/hr. The fire was extinguished in three hours.
March 15	**Spray of water to SFP of unit 4** It was started from the top by releasing water from helicopter, in fact the ponds, 12 x 10 meters, were not an easy target for ground-based fire pumps. The arrival of a concrete pump with 58-metre boom on March 22 enabled more precise replenishment of SFP in units 1, 3 & 4, suspecting that the SFP of unit 4 had damaged walls. In unit 2 the spent fuel pool has been topped up internally via the FPC system.
March 16 08.37	**White smoke from unit 3** A large quantity of white smoke was coming out from unit 3 reactor building
March 18 10,00	**Common spent fuel pool is filled with water** It was confirmed that the common spent fuel pool for Fukushima Daiichi (which is separated from the pools of the individual reactors) was filled with water and no abnormalities were observed in the spent fuel dry cask storage buildings

March 18	**Opening of holes in the roof of the unit 5 and unit 6** Work was begun to open holes in the roof of the unit 5 and unit 6 reactor buildings in order to keep hydrogen from accumulating within the buildings
March 18	**Rating of the accident at level 5** NISA raised the severity rating of the crisis at the Fukushima No. 1 nuclear power plant at level 5 of INES
March 22	**Connection of ac-power supply to all units onsite** An external source of ac-power was made available onsite (cable) and was connected to the power centers of all units enabling to start the works to restoring electricity to systems and equipment after verifying the operability of the circuits and electrical equipment. To make available onsite an external source of ac-power has taken a significant long period of time (about 12 days), it is important to understand the difficulties encountered considering the overall scenario. Tepco informed that once the control rooms would have been operational, water levels could have been checked as well as temperatures in the fuel storage pools, and try to resume the normal cooling of those pools. Tepco also explained that radiation levels inside the plant were so high that normal access was still impossible, therefore they were giving priority to removing contaminated water so as to allow better access. Considering the complete blackout in the control rooms up to March 22, it has to be analyzed how the operator was able to get information regarding main reactor and containment parameters. This extreme poor conditions could have led to mistake regarding reactor and containment parameters. We also notice that in the news made available by Japanese organization there is no evidence of the existence of an Emergency Control Room. It should be verified.
March 22	**Restored of electrical power to Control Room of unit 3** The first Control Room to be powered with recovering of lighting and operability of instrumentation (to which extent?) was the unit 3 on March 22. We have no exact information about the time when the operability of control room was lost (we expect due to loss of dc power)
March 24	**Restored of electrical power to Control Room of unit 1** We expect that the operability of control room was lost due to loss of dc power,

	but we do not know when it happened.
March 25	**Replacement of seawater with fresh water to unit 1 and unit 3** Fresh water from a nearby dam was available and replaced the seawater in the cooling functions of unit 1 and unit 3
March 26	**Restored of electrical power to Control Room of unit 2** We expect that the operability of control room was lost due to loss of dc power
March 26	**Replacement of seawater with fresh water to unit 2** We expect that the operability of control room was lost due to loss of dc power
March 29	**Restored of electrical power to Control Room of unit 4** We expect that the operability of control room was lost due to loss of dc power
March 30	**Status of Reactor Cooling** Since March 30 7-8 m^3/hour were being injected into each reactor. The decay heat production is slowly reducing form that time. The cores remained partly uncovered. Tepco estimated on 27 April that 55% of the fuel rods in unit 1, 35% in unit 2 and 30% in unit 3 were damaged. After almost three weeks, the decay power from the fuel in the reactor cores was estimated by France's ISRN as 2.5 MWt in unit 1 and 4.2 MWt in units 2 & 3.
April 2	**Crack in the concrete of a service pit of unit 2** It was confirmed the presence of a crack in the concrete of a service pit of unit 2 with leakage to the sea of highly contaminated water. The leakage was stopped on April 6 as reported by Tepco.
April 3	**Recover of external power supply** Power supply to temporary motor-driven pumps was switched to external electric grid for unit 1,2 and 3.
April 6	**Inertization of PCV of units 1 and 3** Injection of Nitrogen in the primary containment of unit1 and unit 3 was initiated to prevent H2 explosion
April 12	**Rating up of the accident to level 7** Japan’s Nuclear and Industrial Safety Agency (NISA) announced a new rating for the accident at the Fukushima Daiichi Nuclear Power Station of Level 7

	(major accident) on the International Nuclear and Radiological Event Scale (INES) of the IAEA. Level 7 is the most serious on the scale, and had previously been assigned only to the Chernobyl accident in the former Soviet Union in 1986.
May 10	**Overall situation** - All three units have damaged fuel and low water levels. - The fuel remains essentially contained - Primary containment of unit 1 flooded up to the reactor core top level - Leaking of contaminated water from unit 2 is observed where the containment appears to be breached. - Cooling of fuel in all locations is still ensured by an ''open system''. It means that it is provided from external sources, using fresh water and pump trucks, - Utility continues working to establish a stable heat removal path to external heat sinks. - The presence of radioactive water in the turbine buildings is hampering the work to re-establish the operability of plant systems. - Access has been gained to unit 1 reactor by MPP workers starting from May 9 having installed an air filtration system in unit 1 reactor building to lower the levels of airborne radioactivity and enable access (need to recover a heat exchanger for the RHR circuit). - Spent fuel ponds in units 3 & 4 still need to be topped up repeatedly (via internal piping for units 2 & 3 and by concrete pump with boom for unit 4). - The pond heat exchangers for units 1, 3 & 4 are very damaged. - There is concern about the structural integrity in unit 4 of building structures supporting the spent fuel pool.

Tsunami Arrival at Fukushima Daiichi

Summary of timeline of main events in the units 1-4 of Fukushima Daiichi NPP

Unit 1	Unit 2	Unit 3	Unit 4
March 11 - 14:46: Tohoku earthquake hits Fukushima Daiichi NPP **March 11 - 15:41** Station Blackout due to tsunami hitting Fukushima- Daiichi NPP **March 11- 16.36:** Isolation condenser stops **March 12 - 10.17:** Venting of the Containment **March 12- 15.36:** H2 explosion on service floor **March 12 - 20.20**: Seawater injection **March 13:** Seawater injection in the primary containment **March 24:** Restored of electrical power to Control Room **March 25:** Replacement of seawater with fresh water **April 6 :** Inertization of PCV	**March 11 - 14:46:** Tohoku earthquake hits Fukushima Daiichi NPP **March 11 - 15:41:** Station Blackout due to tsunami hitting Fukushima- Daiichi NPP **March 13 - 11.30:** Venting of the Containment **March 14 - 13.25:** Isolation pump stops **March 14 - 16.34:** Seawater injection **March 15 - 06.14:** Explosion in the PCV **March 26:** Restored of electrical power to Control Room **March 26:** Replacement of seawater with fresh water **April 2 :** Crack in concrete pit	**March 11 - 14:46:** Tohoku earthquake hits Fukushima Daiichi NPP **March 11 - 15:41:** Station Blackout due to tsunami hitting Fukushima- Daiichi NPP **March 13- 05.10:** Isolation pump stops **March 13 - 08.41:** Venting of the Containment **March 13 - 13.12:** Seawater injection **March 14- 11.01:** H2 explosion on service floor **March 16 - 08.37 :** White smoke **March 22 :** Restored of electrical power to Control Room **March 25:** Replacement of seawater with fresh water **April 6 .** Inertization of PCV	**March 11 - 14:46:** Tohoku earthquake hits Fukushima Daiichi NPP **March 11 - 15:41:** Station Blackout due to tsunami hitting Fukushima- Daiichi NPP **March 14 -04.08**: High water Temp. in SFP (84 °C) **March 15 - 06.00:** H2 explosion at Spent Fuel Pool **March 15 - 09.40:** Fire in the SFP **March 15:** Spray of water to SFP **March 29:** Restored of electrical power to Control Room

6. Spent Fuel Pool issues

The problem of the Spent Fuel Pool appeared when they were found to be depleted in water. The low water levels should have been determined by evaporation due to the elevated temperatures caused by the loss of cooling circulation, especially in heavily-loaded unit 4.

In **unit 4**, at about 6 am on March 15, there was an explosion in the top part of the building, near the fuel pond, which destroyed the top of the building and further damaged unit 3's upper structure.
Probably the uncovered spent fuel reached the temperature to get oxidation of the cladding and production of H2. The water level dropped due to evaporation, if not boiling, caused by the high heat load (3 MW) from 1331 fuel assemblies once circulation ceased.
A few hours after the explosion there was a fire and soon after the radiation level near the building reached 400 mSv/hr, apparently from this source. The fire was extinguished in three hours.

The focus from March 15 was on replenishing the water in the spent fuel pools (SFP) of units 1, 2, 3 and 4, through the gaps in the roof and cladding, using seawater.
These ponds, 12 x 10 meters, were not an easy target for ground-based fire pumps, but the arrival of a concrete pump with 58-meters boom on March 22 enabled more precise replenishment in units 1, 3 & 4 that had damaged walls. Unit 2 pond has been topped up internally via the recirculation system.
On March 25, water from a nearby dam started to be used instead of seawater.
At the time of writing the water supply to SFP of units 1, 3 and 4 is ensured by water spray from concrete pumps. For unit 2 the water is injected through the fuel pool cooling line by external temporary motor driven pump.

The pond at unit 4 is the main focus of concern now. It needs continuous top-up with water, and over 100 m^3 of water is being added daily, but at the same time there is concern about the structural strength of the building, which has been weakened either by the earthquake or the hydrogen explosion.
The fuel pond when full of water is a mass of about 2000 tons.
Analysis of radionuclides in water from the used fuel pool of unit 4 shows that some of the fuel assemblies may be damaged, but the majority are intact.

On Marc 19 the residual heat removal pumps for units 5 & 6 ponds were restarted as power was restored, and temperatures where under control.

The central spent fuel pool holds about 60% of the used fuel on site. Due to the station blackout and consequent loss of circulation-cooling system, the temperature increased up to 73°C by the time the cooling was restored on March 24.

7. Accident management

The accident management on Fukushima Daiichi has been carried out in conditions which have never been considered possible before.

The massive disaster which caused the Fukushima Daiichi accident has transcended all previous foreseen severe accident scenarios.

After the arrival of the Tsunami on the site the conditions have been the following:

- Site flooded by the tsunami (a few meters of water)
- Total station blackout for units 1, 2, 3 and 4 (including loss of dc-power soon after due to consumption or loss of batteries)
- Loss of ultimate heat sink
- Lack of relevant information on plant conditions (due to un-powered control rooms)
- Severe accident conditions affecting the reactors of 3 units
- Critical conditions affecting the cooling of spent fuel in the ponds of four units
- Situation getting rapidly more and more critical onsite for the high radiation field, increasing air contamination and high temperature in the buildings with consequent impossibility to have access
- Damages on the territory due to earthquake first and tsunami after
- State of stress and tension of staff on site due to concern for private suffered damage or injury and the crisis in progress on site.

In these conditions, and trying to follow the accident management guidelines, and getting the necessary approval for actions not predefined in the accident management (e.g. the decision to inject sea water not envisaged by the accident management, and implemented with some excessive delay for unit 1 was finally ordered by the Government), the crises team and the field operators have done the best to manage the status of the plant and try to ensure the necessary actions to terminate the progression of the severe accident and to face the destructive events due to explosions on all units.
We express the deepest sympathy and respect to the emergency workers onsite and praise their courage, composure and resilience.

It appears quite clear that the management of the accident at Fukushima Daiichi has been carried out on the basis of insufficient, or poor, information about the status and values of the reactor and containment parameters.
No information are available about the available emergency control rooms and safety parameters display systems.
The operator has taken a significant number of decisions and actions to mitigate the evolution of the accident.
The timeline of events as reported in chapter 4 gives a clear picture of the complexity and difficulty of the evolution of accident conditions on the involved units and their management.
The severe conditions and consequent impact onsite and outside have been determined in the very first part of the accident (2-3 days).

We have almost no information on the organizational aspects of the accident management onsite and the way it was carried out: the composition of the site crisis management team, the available number of experts, how they were grouped to follow the evolution of accident on the four units, the support received from outside, the communication system, etc..

The Severe Accident Management Guidelines were available and they need information of status of reactor and containment parameters to be implemented in addition to the availability of systems and equipment.
Both these aspects were highly critical in Fukushima due to unavailability of the control rooms for long time and due to the inoperability (station blackout) of all safety and non-safety systems onsite.
Therefore the crisis team needed first to organize the onsite temporary source of electrical energy (relying also on the external support) and equipment and then to establish connections (alignment) with accessible reactor systems trying to get the needed functions performed.
The difficulty to finalize successfully these actions, the delays and the obstacles created by the onsite destructive events are to be examined and studied carefully to learn from them.

At the moment the available data allow us to get aware of the overall evolution of the accident and the major facts and start to get confident with some emerging issues. Many questions are open. Available detailed information is not sufficient to perform a study of the accident management and in some cases, for what we know, some data appear to be also not consistent.

8. Radiological impact

The main radionuclide released, among the fission products generated in the fuel, is the volatile iodine-131, which has a half-life of 8 days. It has been released in both to air and to water. I-131 decays to inert and stable xenon-131. In one month the released iodine diminishes to one sixteenth of original activity.
The other main volatile radionuclide is caesium-137, which has a much longer half-life (30 years) and may contaminate land for some time.

As reference the ICRP (International Commission for Radiological Protection) establishes the effective dose limit of 1 mSv/yr for the public, as average in 5 years.
This limit does not include the effective dose that the public receives from the natural background. The world's average annual effective radiation dose for the public due to natural background is 2,4 mSv/yr. In Italy the average natural background radiation dose is 3.2 mSv/yr.
No health effects have been observed for exposure up to 100 mSv.

Radioactive releases - After the hydrogen explosion in unit 1, some radioactive cesium and iodine were detected in the vicinity of the plant, indicating fuel damage. This material had been released via the venting from the primary containment.
Release of I-131, Cs-137 and Cs-134 took place during the following two weeks, particularly following the explosion at unit 3 on March 14 and the apparent rupture of suppression chamber of unit 2 on March 15.
The hydrogen explosion in unit 4 involving the spent fuel pond on March 15 added further release of radionuclides.
On March 17 NISA raised the dose limit for Fukushima workers from 100 to 250 mSv /year after consultation with health experts, to allow work to be carried out.

IAEA reported on March 19 that airborne radiation levels had spiked three times since the earthquake, reaching values of 400 mSv/hr, but it had stabilized since March 16 at levels significantly higher than the normal levels, but within the range that allows workers to continue on-site recovery measures.

NISA reported 12 mSv/hr dose rate at the site boundary early on March 14th, then 3.4 mSv/hr mid March 16. Late on March 24 it was about 0.2 mSv/hr at the front gate, having been ten times that a few days earlier.
Steady decrease has been maintained: on April 4 it was 0.12 mSv/hr at the front gate and 0.05 mSv/hr at the west gate. On April 17 dose rates at eight monitoring points around the boundary ranged from 0.01 at the north end to 0.19 mSv/hr at the south.
Monitoring beyond the 20 km evacuation radius showed on April 13 one hot spot location 24 miles north-west, around Iitate, with up to 0.266 mSv/day dose rate (the safety limit set by the government in mid-April for public recreation is 0.09 mSv/day).

The presence of radioactive isotopes Pu-239, Pu-240 in the soil is within the range of Japanese background. Some higher activity of isotope Pu-238 around the plant has been measured (5,4 x 10^{-1} Bq/kg about 3,6 times the "historical" background).

Overall release - On April 3 NISA's report to IAEA gave their estimation of total release of I-131 and Cs 137 during the accident. In the table below are reported also the estimation of the Japan Nuclear Safety Commission (NSC) which differs from the NISA estimation:

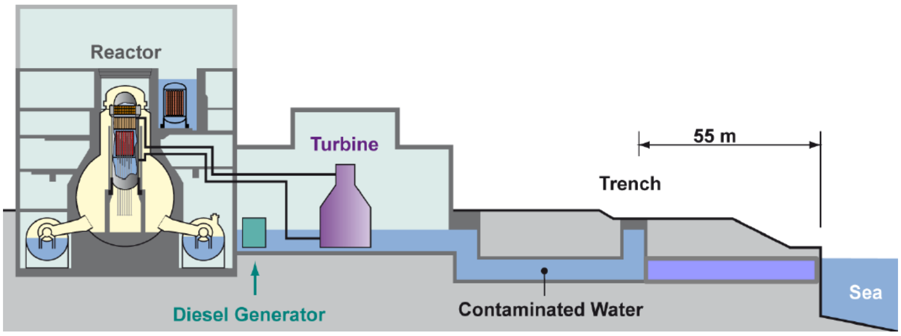
Total release of I-131 and Cs-137*		
Radionuclide	**NISA estimation****	**NSC estimation*****
I-131	**130 PBq**	**150 PBq**
Cs-137	**6.1 PBq**	**12 PBq**

* The release of correspondent radionuclide in Chernobyl accident were respectively: I 131 = 1800 PBq, Cs 137 = 85 PBq
** estimation by NISA based on numerical analysis of accident evolution
*** estimation by NSC based on monitoring data estimating backward the amount of release
PBq = 1E15 Bq

These estimations resulted in the re-rating of the accident to INES level 7.

Tepco has been spraying a dust-suppressing polymer resin around the plant to ensure that fallout from mid March is not mobilized by wind or rain. This spray will continue on the site by late June. The highest radiation levels on site come from debris left on the ground after the explosions at units 3 & 4. Some rubble near unit 3 is giving the highest dose rate of some 300 mSv/hr, while other debris patches are at 30-40 mSv/hr. Much of the debris around the former office building has been removed, and it has started clearing the rubble around the units 3 and 4. This is further reducing ambient radiation levels.

Management of contaminated water - Removing contaminated water from the reactor and turbine buildings, along with contaminated water in trenches carrying cables and pipes, had become the main challenge since the last week of March.
In between April 1 and 6 some 520 m^3 of contaminated water from unit 2 (via trenches) with 4.7 PBq of activity leaked into the sea until the source was sealed.



By the end of March all storages around the four units - basically the main condenser units and condensate tanks - were largely full of contaminated water pumped from the buildings.
Therefore with government approval, Tepco over April 4-10 released to the sea about 10,400 cubic meters of slightly contaminated water in order to free up storage for more highly-contaminated water from unit 2 (reactor and turbine buildings) which needs to be removed to

make safe working conditions. NISA confirmed that there was no major change in radioactivity levels in the sea as a result of the 0.15 TBq discharge.
The highly-radioactive water from unit 2 turbine hall basement was then transferred to the waste treatment plant (nearby unit 4). The water contains 3 TBq/m^3 of I-131 and 13 TBq/m^3 of Cs-137.

Tepco announced to complete the construction of a second waste treatment facility by June to receive another 15,000 cubic meters of contaminated water from unit 2 and an additional 45,000 cubic meters of less-contaminated water from turbine buildings of units 1 and 3.
On April 28 there was about 25,000 m^3 of contaminated water in unit 2 turbine building, 20,500 m^3 in unit 1 and 22,000 m^3 in unit 3. Once decontaminated the water will be used for re-injection.

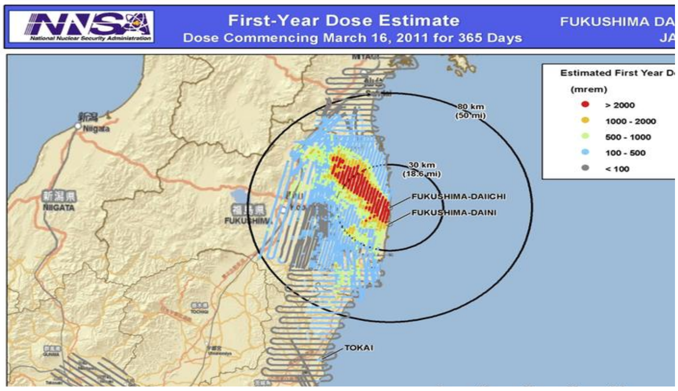
Tepco has installed double-layer silt barriers on the inlet canal and in front of seawater inlet bar screens of units 1-4 to impede leakage to the sea. Also, steel plates have been installed on the inlet bar screen of unit 2.

Radiation exposure onsite - About 250 workers have been working onsite during the accident. On March 24 three contractors laying cable in unit 3 received a dose of more than 170 mSv, two suffering beta radiation burns on their legs from contaminated water.

By May 3, 30 workers had received doses over 100 mSv, two of them over 200 mSv, and none had reached 250 mSv. No radiation casualties (acute radiation syndrome) had been reported, though higher than normal doses are being accumulated by several hundred workers on site.

At beginning of May Tepco installed an air filtration systems to clean up the air inside unit 1 reactor building and enable easier access. On May 9 the first workers gained access to the RB of unit 1, the ambient radioactivity level having come down from 4.8 Bq/cm^3 to 0.0197 Bq/cm^3.

Public exposure - Estimation of *external* doses to population at different distances from the NPP in one year have been performed first by French Institute IRSN and also by US Department of Energy and Japanese Ministry of Education, Culture, Sport, Science and Technology.
The results are described by dose maps as shown in the figure aside. It appears that the doses are no more in the range of ''low doses'' according to UNSCEAR definition (United Nations Scientific Committee on the Effects of Atomic Radiation). The French report (ref. /28/) shows significant values of projected doses some above 200 mSv in the north-west fallout sector and even beyond the 20 km evacuation zone. These dose values do not consider the doses received during the accident (plume immersion, inhalation of particles) or to be received from internal contamination and ingestion of contaminated foodstuff. The total estimated projected effective doses could be much higher.
The number of Japanese people living in the most contaminated area outside the 20 km evacuation zone is estimated to be 70.000 including 9.500 children between 0-14 years.



9. Tepco remediation plans

On April 17 Tepco has published a roadmap of remediation activities covering the initial period of time up to the end of the year. It is made of two steps: step 1 of 3 months and step 2 with a duration of 6- to 9-month dealing with the disabled Fukushima Daiichi reactors up to the end of the year.
The target of the roadmap is to achieve a continuous reduction of the radiation dose and achieve control of radiation release. The plan address the following specific actions:

Reactor core cooling - The actions envisage to flood the containment vessels up to the level of the top of the fuel, and nitrogen injection will be continued. In unit 2 the damaged containment will be sealed with grout, before similarly flooding. New heat exchanger circuits will be built for all three units. Cold shutdown target in 6-9 months. The plan does not mention, at the moment, any removal of fuel from the reactors.

Spent fuel pools - improve the water injection and recirculation to all SFP of four units, restore the heat removal with new or repaired heat exchangers. Reinforced the structures under the SFP of unit 4. Later transfer of fuel to the central storage should start.

Minimizing atmospheric release - Dust-suppressing polymer resin will continue to be applied, and debris removed to improve working conditions on site. A light temporary structure (see fig. aside) will then be built over reactor buildings 1, 3 & 4, followed by a more substantial structure.

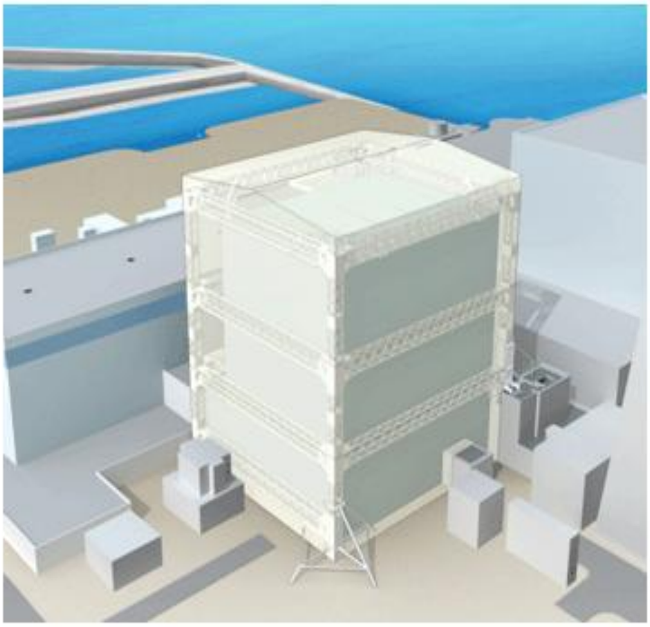


Image of the cover for the reactor building of Unit 1, Fukushima Daiichi Nuc Power Station

Treatment of contaminated water - Installation of additional storage capacity and new treatment plant to enable recycling with focus on unit 2.

Decontamination for return of evacuees - Monitoring will be expanded and the evacuation zone will be decontaminated where required so that evacuees can return as soon as possible.

Grouping of Japanese and other international company are elaborating proposal for future approach to decommissioning. One approach is to remove the fuel and then seal the units for a few decades before dismantling (to get low activation level in the materials).
Tepco has already allocated $2.53 billion in its accounts for decommissioning of units 1 to 4.

10. Emerging considerations

The Fukushima accident has brought at the attention of utilities, designers and regulators an extremely important set of issues which need to be elaborated.

While the NPP structures seem, in general, to have successfully withstood the seismic event, the defense against the seism-generated tsunami has failed, due to underestimation, incurring in a common-caused loss of ac-power causing, after a partial initial operation of steam driven reactor cooling system, a loss of cooling function on four units!
These severe conditions have been faced by injecting seawater with temporary mobile equipment and performing other accident management actions.

The accident in Fukushima shows a peculiar feature: it is highlighting a number of deficiencies and weaknesses which need to be fully analyzed. The issues cover a very wide spectrum of technical areas and responsibilities, impacting the activity of designers, operators and regulators.

At the moment while it is still too early to find full lessons learned and place any responsibility, It is already possible to elaborate some specific observations and get some first important indications from the Fukushima accident. The consideration mentioned here are developed with the aim to contribute to this process.

in doing that we do not intend to criticize any involved party as we are aware that things that seem inherently obvious now certainly weren't so obvious before the accident even though some complacency has been pointed out already by recognized worldwide experts.

The indications emerging from Fukushima accident impact both ''new design'' and ''operating NPP''. While for new design it is more comfortable, in terms of time constraints, to feedback the learning from Fukushima event, the priority in the use of ''lessons learned'' is for the operating NPP and calls for immediate review and re-assessment actions.

10.1 Considerations for NPP in operation

The operating NPP which should first benefit from lessons learned in Fukushima accident undergoing a safety re-assessment for pre-defined and agreed safety issues. The indication reported below refers with priority to the following topics:

- Site External Events
- Multi units site
- Spent Fuel Pool
- H2 Management
- Total Blackout
- Loss of Heat Sink
- Severe Accident Management

Site External Events	1	A re-assessment of the basis and approaches to identify the external events (natural and non) as basis of the design of the operating NPP and verify the dimensioning of related defense needs to be carried out.

	2	It would be opportune to carry out a comprehensive and systematic analysis of the evolution of postulated accidents due to external events. This analysis should verify the adequacy of safety features, of the effectiveness of the accident management in beyond design conditions, availability of systems and resources, its preparedness and finally ascertain the capability of the NPP, including operators, to face successfully the postulated accident conditions.
	3	The analysis of postulated scenarios due to external events should give evidence of the adequacy of the implemented defense in depth (redundancy and diversification to minimize risks of common mode failure due to EE) assess the margins and exclude the existence of possible cliff-edge effects.
Multi-unit site	4	Common failure of more units on the same site due to extreme conditions caused by external events should be investigated, as first step, to show the capability to manage accident conditions in more units and be prepared for that.
	5	As second step provisions should be taken to reduce the risk of common failure induced by external events which can led to simultaneous severe accident conditions in more units
Spent Fuel Pool	6	A re-assessment of the conception of the SFP and its protection and response following accident scenarios caused by external events needs to be performed.
	7	Potential interactions between the evolution of severe accidents affecting the reactor and the safe status of the SFP (and vice-versa) should be investigated in order to identify weaknesses to be resolved.
	8	The benefit of having limits on the quantity of spent fuel assemblies to be stored in the SFP could be assessed in order to minimize the consequences of potential accidents affecting the SFP and evolving towards severe conditions.
H2 Management	9	The effectiveness of existing measures for H2 management in operating NPP should be re-assessed for severe accident conditions and new postulated scenarios. Making reference to pre-defined severe accident scenarios (e.g long lasting SBO) it is needed to re-assess basis, assumptions and analysis performed to design the H2 management system and related accident management provisions.
	10	The provision taken should ensure effective control avoiding explosion inside containment. Existence of robust passive system for H2 control should be verified.

	11 Conditions needing containment venting with release of H2 should be examined and verified as to avoid H2 explosion.
Total Station Blackout	12 It is considered necessary to assess the operating NPP response, including accident management, to long lasting Station Blackout (SBO) in the light of Fukushima event. 13 The adequacy of accident management guidelines including identification, and availability, of needed mobile equipment, tools and resources should be checked and revised as needed. 14 The preparedness to implement the required SAMG should be verified 15 The habitability and reliability of MCR, ECR and other technical support centers to monitor the accident evolution and manage the accident should be checked. 16 The availability of onsite equipment and of prompt external support to supply needed equipment and materials, and their effectiveness in the ongoing accident scenario, should be verified. 17 In doing that it should be considered the simultaneous additional damages produced onsite by the potential external initiator of the SBO and also the damages produced on the territory which can interfere with the management of the accident.
Loss of Ultimate Heat Sink	18 It is considered necessary to assess the NPP response & preparedness to conditions of long lasting loss of ultimate heat sink (UHS). 19 The adequacy of accident management guidelines including the identification, and availability, of needed mobile equipment, tools and resources should be verified. 20 The preparedness to implement the required accident management guidelines, the timely availability of onsite emergency provisions and external support for supply of needed equipment and materials should be verified. 21 In doing that it should be considered the simultaneous additional damages onsite, and on the infrastructure of the territory around, produced by the initiator of the loss of UHS.
Accident Management	22 The Fukushima accident is going to highlight more and more new aspects having relevance for the elaboration and requirements of the severe accident management guidelines.

23 The SAMGs of operating NPP should receive a re-assessment in the light of Fukushima event. In particular the SAMGs should consider extended duration of postulated severe scenarios (e.g. long lasting station blackout and long lasting loss of ultimate heat sink).

24 The adequacy of the instructions and their basis, the way to take prompt decisions, the effective availability of materials, equipment, resources and external support should be verified. To be also verified the preparedness from operator side to face and manage extreme accident scenarios.

25 In performing this review the effective availability of the Emergency Control Room and related control function should be verified (reliability of electrical supply, display of reactor and containment key parameters, habitability, etc.)

26 The Accident Management Guidelines together wit the preparedness of the operator and the availability of needed equipment and control center should be verified as being able to ensure the recover and control of the NPP status before core-damage.

In addition for Operating NPP we consider of particular relevance to reinforce the objective and scope and quality of the activities related to Periodic Safety Review (PSR) and Plant Life Extension (PLEX). In particular the following aspects could deserve attention from the Operator and Regulator side:

Periodic Safety Review (PSR) - There is the need to reinforce the scope, the quality and the effectiveness of periodic safety review (PSR) for operating NPP.
In addition to evaluate the NPP safety performance and operating experience, it should give evidence of the level of adequacy of the safety conception and provisions compared to current safety requirements and the need for continuous improvement.
The PSR should better define its objective related to back fitting the NPP according to current safety levels.
It could be effective to review during the periodic safety review the dimensioning design values of the NPP on the basis of the most recent advances and knowledge about external events and internal events.
The safety review should be systematic and take into account the international experience and the specificity of the operating NPP (siting, design, external events, operating records, etc.).

Plant Life Extension (PLEX) - Need to review the adequacy and effectiveness of requirements to be met for PLEX.
PLEX should not only refer to assessment of aging of SSC but should also give appropriate importance to the safety level of the facility as referred to current implemented safety standards and requirements.
For PLEX comprehensive safety re-evaluation shall be conducted by the Licensee and reviewed and approved by the Regulator.

10.2 Considerations for new design

We know that the current new NPP designs already provide means to deal with a number of shortcomings from Fukushima accident; nevertheless it is worthwhile to put them at the attention of involved parties.
The considerations reported below, as preliminary learning from Fukushima accident for new design, are grouped under the following topics:

- Siting of NPP and External Events
- Multi-unit site
- Seismic Hazard and Tsunami
- Defense in Depth
- Spent Fuel Pool
- Probabilistic Safety Analysis
- Accident Analysis for External Events
- Station Blackout
- Loss of Ultimate Heat Sink
- H2 Management
- Accident Management
- Human Factor
- Reliability and Habitability of the Emergency Control Center
- Use of Experience

Siting of NPP and External Events	1	Sites with less risk of exposure to external severe events should be first considered and primarily pursued while selecting a site.
	2	NPP siting needs to consider all aspects pointed out by Fukushima accident. It is possible that the site screening process could consider new requirements (e.g. minimum distance from sea coast, rivers, lakes and all possible flooding areas).
	3	The assessment of earthquake-induced effects (e.g. tsunami and seiches, landslides and liquefaction) need to receive further effort in order to be carefully and completely performed. This will lead to identify severe risk that can determine the rejection of the site or to adequately identify the design basis of NPP against external events.
	4	The basis and methodologies to identify the external events (EE) need to be revisited, according to learning from Japanese event, and an increased robustness and resilience of the NPP protection against the EE should be ensured.
	5	Once completed the learning process from the Japanese event it could be useful to carry out an in-depth evaluation of content of the IAEA Safety Standards for siting to verify the possible need and opportunity for an appropriate review.

Multi-unit site	6	Interactions among units on the same site should be assessed in particular in accident and emergency conditions.
	7	In general it should be minimized the risk to face scenarios with severe accident (SA) conditions in more units. This should be achieved with high confidence.
	8	More units onsite should apply provisions to avoid, as much as possible common and simultaneous malfunctions due to the same external event.
	9	This provisions could impact the layout and orientation of units on the site, minimum distance between units, diverse design solutions for the emergency features (e.g EDG, heat sink, etc.) between units reducing in such a way the risk of common vulnerability to external events (natural and non).

Seismic Hazard and Tsunami	10	The process of learning from the study of the event (ground motion and tsunami) and the response of NPP Structures, Systems and Components (SSCs) should be fully conducted.
	11	Further elaboration of the understanding, including uncertainties, of the potential link between the seismic event and the magnitude of the induced tsunami for NPP located on the sea coast is needed (considering all relevant factors).
	12	It could be assessed the opportunity that appropriate distances (horizontally and vertically) from coastlines facing offshore active faults and plate margins could be required independently of any technical and economical reason.

Defense in Depth	13	The validity of the defense in depth (DiD) principle is not in question after the Fukushima accident. However the independence between the levels of Did needs to be enhanced.
	14	It is confirmed the importance that a safe design of a NPP should benefit from a systematic and comprehensive application of DiD (for internal and external events) ensuring the existence of balanced defenses with respect to postulated events. This is a key point needing further effort in the application. in particular to eternal events, as it determines the robustness and resilience of the design and its safety systems.
	15	It is pointed out from the Fukushima accident the need to extensively and completely investigate the potential CCF due to external events and consider them in both deterministic and probabilistic safety analysis together with the direct failures

caused by the Initiating Event (IE) on components availability.

Spent Fuel Pool

16 The facts of Fukushima call for a re-assessment of the conception of the Spent Fuel Pool, the lay-out, related safety systems and auxiliaries and its management.

17 Possible interaction of accident scenarios affecting the reactor with the safe status of the SFP should be investigated and taking provisions minimizing their probability with high confidence.

18 Provision limiting the quantity of spent fuel pool stored in the SFP could be considered in order to maintain potentially low the severity of accident scenarios dealing with SFP.

Probabilistic Safety Analysis

19 It is confirmed the importance to ensure, and verify, the systematic implementation of the probabilistic safety analysis with the objective to identify weaknesses in the design, siting and layout of NPP as referred to external events.

20 It should be verified and confirmed with high confidence the completeness in terms of analysis of all possible sequences.

21 On the other side the use of PSA, whose objective is to identify - first - all potential accident sequences and then to eliminated or reduce in probability those with higher risk (compared to defined safety goals), should be enhanced in terms of systematic and comprehensive approach, mostly in the review of exclusion criteria on the basis of event credibility.

22 The Fukushima accident is pointing out the need to identify those external events having the potential to generate consequential phenomena which can create severe common failures onsite.

23 The Fukushima accident is bringing at the attention of involved parties the need to further investigate the potential interactions between units during severe accident scenarios

24 The systematic use of level 2 PSA to study the phenomena following the core damage and the containment behavior in severe scenarios should be ensured to identify potential relevant issues and to support the definition of appropriate SAMGs.

Accident Analysis for External Events

25 The safety analysis of NPP response to a design basis external event (EE) needs to be performed and carried out according to the requirements of the ‘’accident analysis’’ showing the capability of the NPP to withstand the EE, assess the margins and exclude possible cliff-edge effects.

26 This accident analysis of EE should be performed taking into account all failures directly determined by the external initiating event, the consequences on functional and structural integrity of safety and non-safety SSCs and the potential interaction between failed systems (or structures or equipment) and the operability of required safety systems.

27 As an example the seismic event should not be ruled out only by designing the safety SSCs against the seism, it is necessary to perform also an accident analysis which will allow analyzing the scenario following the seism (including all consequences) and verifying that the required safety functions are ensured and the NPP (or other NF) is maintained in a controlled status.

Station Blackout

28 A station blackout (SBO) event with loss of all electrical sources (external and internal) for long period of time should be considered demonstrating the effectiveness of provisions taken to manage such event avoiding significant radiological impact (accident management procedures, monitoring capability, suitability of physical access to critical hardware of the NPP, availability of resources and equipment, etc.).

29 The Fukushima accident has pointed out the importance to consider in the analysis of SBO the direct consequences, in terms of damages and impaired safety provisions, caused by the external events (natural and non) that can cause the SBO.

30 In terms of prevention it should be given evidence of having taken all provisions during siting and designing phases to reduce the probability of such long lasting SBO (LLSBO).

Loss of Ultimate Heat Sink

31 The capability of a NPP to face without severe consequences long lasting loss of ultimate heat sink should be analyzed considering the required cooling functions to be ensured.

32 The potential scenarios with loss of ultimate heat sink should be investigated, identified and provisions taken at design and at accident management level to face those extreme condition avoiding severe accident conditions.

H2 Management

33 The management of H2 in a NPP following an accident is a well-known and addressed issues in the design of NPP.
The effectiveness of design provisions to manage the H2 in a severe accident condition should be revisited again in the light of Fukushima event.

34 It could be opportune to review the basis and assumptions characterizing the production, rate of production, spatial distribution and the effectiveness of measures taken to manage the H2 distribution and concentration avoiding H2 explosion inside the containment.

35 The effectiveness of H2 management in severe scenarios characterized by persisting station blackout should be ensured.

36 Adoption of passive system for H2 control should be foreseen and required.

37 Conditions needing containment venting with release of H2 should be considered and examined to verify the basis and monitoring tools for operator actuation and the related risk for H2 explosion while venting.

Accident Management

38 The Accident Management (AM) guidelines-procedures and related tools need to be revisited despite additional requirements and new postulated scenarios.

39 The re-consideration should verify the validity of the AM guidelines in front of postulated scenarios (including new ones) and in terms of availability and accessibility of information, materials, equipment, necessary resources and preparedness to face successfully the postulated emergency scenarios.

40 The interfaces with damages to infrastructures and population around the site caused by the external events should be considered as factors affecting the accident management onsite.

41 The AM should consider in a comprehensive way scenarios related to the reactor core and to spent fuel pool (SFP). Possibility of interaction should also be considering depending on the specificity of the design and layout.

42 To facilitate the accident management in scenarios of extreme difficulties (e.g. LLSBO) , it could be useful to re-think (at design stage) the layout of some relevant equipment in the reactor building and also in other buildings to make easier the access to them, to check their status and also to power them with temporary groups.

43 The effective availability of the needed emergency control center should be ensured. That is the Emergency Control Room needed for the AM, receiving the key information from the NPP status, being highly independent and protected from the onsite environmental conditions during the crisis.

Human Factor	44 The provision to be taken to ensure the most appropriate working conditions (and shifts) for operators during the crisis in order to minimize stress, risk of errors, as well as minimizing the radiation exposure during manual actions in field, need to be assessed based on the postulated severe scenarios and their potential consequences. 45 Much more is expected to be learned from the Fukushima event once will be available a comprehensive analysis of the human factor during the management of the accident highlighting the positive and negative facts.
Reliability and Habitability of the Emergency Control Center	46 The validity of today conception and provisions for layout, access, habitability and emergency supply of MCR and ECR against the experience learned from Fukushima accident should be reconsidered. This action should be carried out also for the Technical Support Centre (TSC). 47 The availability and capacity of power supply (batteries and temporary emergency groups) to the ECR during severe scenarios shall be ensured with high level of reliability by robust design and by appropriate AM actions in all postulated severe scenarios including the event of LLSBO. 48 It could also be examined new alternative conceptions of the ECR using advanced technology with the intent to increase its functional availability, habitability and effectiveness (display of key parameters, actuation of key operator actions, highly reliable and resilient electrical supply system, internal working conditions fully protected by the consequences of the accident, etc.).
Use of Experience	49 It is our convincement that there is a need to improve the use of experience and learning from precursors, avoiding complacency (the event in the French NPP Blayais in 1999 could be considered a precursor of Fukushima). 50 Learning from experience is a key aspect of the nuclear safety culture and is required by regulators in all country having a nuclear program in operation. 51 It appears that the implementation of this requirement should be reinforced, and enforced, considering it as an important factor contributing to the continuous improvement of nuclear and radiation safety.

11. EU Stress Tests

In response to discussions at the Council of the European Union for Energy held on 21st March, a WENRA task force has developed objectives and scope of so called ''stress test" to be applied to NPP in EU.
The aim of the work is to see what improvements to nuclear safety may be appropriate in light of the Fukushima nuclear accident, as far as it is understood.
The "stress test" is defined as a targeted reassessment of the safety margins of NPPs in the light of the events which occurred in Fukushima.

The proposal from WENRA has been presented to the European Nuclear Safety Regulators Group (ENSREG) meeting in middle of May. In particular a document '' EU ''stresses Tests'' specifications (available on the ENSREG website) has been issued by WENRA and adopted by ENSREG as basis for the safety assessments,

The WENRA document contains a general section presenting the definition of the 'stress tests', their technical scope and the process to perform the 'stress tests' and their review.
The document sets out the general information required from the licensees and the issues to be considered by the licensees for each considered extreme situation.

This reassessment will consist in a verification of the preventive measures and in an evaluation of the response of a nuclear power plant when facing a set of extreme situations, chosen following a defense-in-depth logic (initiating events, consequential loss of safety functions, severe accident management issues). The preferred approach is deterministic.
For a given plant, the reassessment will report on the effectiveness of the preventive measures and on the response of the plant, noting any potential weak point and cliff-edge effect, for each of the considered extreme situations.
The reassessment is based on the existing safety studies and engineering judgment to evaluate the behavior of a nuclear power plant when facing the extreme situations.

The results of the reassessment may indicate a need for additional safety provisions being technical or organizational (such as procedures, human resources, emergency response organization, use of external resources).
It remains a national responsibility to take any appropriate measures resulting from the reassessment.

The licensees have the prime responsibility for safety. Hence, it is up to the licensees to perform the reassessments, and to the regulatory bodies to independently review them.
During the regulatory reviews, interactions between European regulators will be managed through WENRA or ENSREG as needed.
The schedule envisages the following:

- National Regulator send requirements to Licensee : June 1st 2011
- Final Licensee Report: October 31, 2011
- Final National Report: December 31, 2011
- EC consolidate Report to EU council: June 30, 2012

Progress reports will be available in advance on the indicated deadline.

12. References

1. Tepco relases and reports on status of NPP in Fukushima Daiichi
2. NISA briefing relases on status of NPP in Fukushima Daiichi
3. WNA updates on Fukushima Daiichi accident
4. Earthquake reports and status of NPP in Fukushima - JAIF
5. The Possible Influence of the Fukushima Daiichi NPP Accident Caused by the Eastern Japan Earthquake Disaster- The Federation of Electric Power Companies, April 4, 2011
6. Fukushima Accident 2011 - WNA – Updates up to May 9, 2011
7. The 2011 off the Pacific coast of Tohoku Pacific Earthquake and the seismic damage to the NPPs – Presentation NISA – JNES , April 2011
8. VGB Power Tech Presentation Tohoku earthquake and tsunami – Consequences for NPP in northeast coast - Mohrbach Linnemann , April 2011
9. Si H. & Midorikawa S., 2000. New Attenuation Relations for Peak Ground Accelerationand Velocity Considering Effects of Fault Type and Site condition. 12th WCEE, Auckland, NZ.
10. Satake K., Sawai Y., Shishikura M., Okamura Y., Namegaya Y., Yamaki S., 2007. Tsunami source of the unusual AD 869 earthquake off Miyagi, Japan, inferred from tsunami deposits and numerical simulation of inundation. American Geophysical Union, Fall Meeting 2007, abstract #T31G-03
11. National Research Institute for Earth Science and Disaster Prevention (NIED). 2011 Off the Pacific Coast of Tohoku earthquake, Strong Ground Motion. http://www.k-net.bosai.go.jp/k-net/topics/TohokuTaiheiyo_20110311/nied_kyoshin2e.pdf
12. Japan Meteorological Agency (JMA). The 2011 off the Pacific coast of Tohoku Earthquake
13. Observed Tsunami http://www.jma.go.jp/jma/en/2011_Earthquake/2011_Earthquake_Tsunami.pdf
14. Tokyo Electric Power Company (TEPCO). The record of the earthquake intensity observed at Fukushima Daiichi Nuclear Power Station and Fukushima Daini Nuclear Power Station (Interim Report). http://www.tepco.co.jp/en/press/corp-com/release/11040103-e.html
15. Tokyo Electric Power Company (TEPCO). Result on the investigation on Tsunami at Fukushima Daiichi Nuclear Power Station. http://www.tepco.co.jp/en/press/corp-com/release/betu11_e/images/110409e9.pdf
16. Port and Airport Research Institute (PARI). Executive summary of urgent field survey of earthquake and tsunami disasters. http://www.pari.go.jp/en/eq2011/20110325.html
17. Japan Nuclear Technology Institute ‘’The 2011 Pacific Coast of Tohoku Earthquake and NPP - April 2011 - T. Yamazaki.
18. Convention on nuclear safety (INGCIRC/449) (1994)
19. Convention on early notification of a nuclear accident (INFCIRC/335) (1986) and convention on assistance in the case of a nuclear accident or radiological emergency (INFCIRC/336) (1986)
20. EU Stress Test specifications – Declaration ENSREG - http://www.ensreg.eu/node/286
21. ICRP Publication 111 - Application of the Commission's Recommendations to the Protection of People Living in Long-term Contaminated Areas After a Nuclear Accident or a Radiation Emergency- 2009
22. ICRP Publication 109 - Application of the Commission's Recommendations for the Protection of People in Emergency Exposure Situations
23. IAEA Safety Standard -Site Evaluation for Nuclear Installations Safety Requirements Series No. NS-R-3, published Thursday, December 18, 2003.
24. IAEA Safety Standard - External Human Induced Events in Site Evaluation for Nuclear Power Plants Safety Guide Series No. NS-G-3.1, published Wednesday, June 05, 2002.

25. IAEA Safety Guide NO. SSG-9 “Seismic Hazards in Site Evaluation for Nuclear Installations” October 2010
26. Course on "National Nuclear Infrastructure and Institutional Capacity" – Introductory Notes – ITER-Consult - 2009
27. Outcomes of the International Technical Meeting "Seismic Safety of Nuclear Power Plants " Tivoli (Rome) - March 2010
28. IRSN - Assessment on the 66th day of projected external doses for populations living in the north-west fallout zone of the Fukushima nuclear accident - Report DRPH/2011-10

Acknowledgements

I want to express sincere thanks to all experts contributing to the preparation of this report:
L. Antola, R. Caporali, F. Gera, V. Lucarelli, G. Maresca, G. Orsini,, Gv Pino, Gs. Pino, R. Romeo, K. Slavcheva, F. Trenta, G. Trenta.
Gratitude is expressed also to all Japanese and international organizations and experts whose information and reports have been taken as reference for this report.

Antonio Madonna