FUKUSHIMA EARTHQUAKE AND TSUNAMI STATION BLACKOUT ACCIDENT

5/28/2012

INTRODUCTION

Japan generated 29 percent of its electricity from nuclear power plants. The facilities are designed to withstand earthquakes and tsunamis that are common in Japan, which generates its nuclear electricity from 54 nuclear power reactors at 17 plant sites. These included 24 Pressurized Water reactors, PWRs, 30 Boiling Water Reactors, BWRs, and 2 under construction. These reactors generated over 44,000 MWe, or about 30 percent of the nation’s electrical demand.

A state of emergency was declared on Friday, March 11, 2011 by Japan's Nuclear and Industrial Safety Agency, NISA at the Fukushima Daiichi (number one) site and later at the Fukushima Daiini (number two) site Boiling Water Reactors, BWRs after a combined earthquake of magnitude 8.9-9.0 on the Richter scale near the east coast of Honshu, and a tsunami event generating a 15-24 m high wave. The earthquake event is designated as the Tohoku-Chihou-Taiheiyo-Oki earthquake.

Official records dating back to the year 1600 inspired the deterministic or mechanistic safety analysis design of the plant to withstand the strongest earthquakes at the 8.6 magnitude level for the Fukushima prefecture. The Jogan earthquake in the year 869 produced a tsunami that reached 2.5 miles or 4 km inland with waves 26 ft or 8 m high at Soma, 25 miles north of the plant site. The plant was built on a 14-23 feet or 4.3-6.3 m high cliff offering natural protection against tsunamis. The tsunami wave more than 14 m (46 ft) high that originated 125 miles (200 kms) to the East, impinged on the 6 m protective wall and drowned the Fukushima Daiichi nuclear power plant site. According to Tepco’s calculations, the maximum probable tsunami at Fukushima was at 5.7 meters. A 1960 contemporary tsunami in Chile that was caused by a 9.5 magnitude earthquake that produced a 10.5 ft high tsunami wave was used as a reference point for an 18-foot or 5.7 m design point, below the 27-ft or 8.2 m event.

Figure 1. Earthquake and Tsunami, March 11, 2011, Japan. Source: Reuters.

The location is 150 miles or 250 km north of the greater urban area of Tokyo inhabited by 30 million people, and 40 miles from the earthquake epicenter in the Pacific Ocean. It is the most powerful earthquake event in Japan since the start of record-keeping in the 1800s. A folk legend describes the Japanese Islands as lying on the back of a giant fish in the ocean that is constantly twitching and trembling.

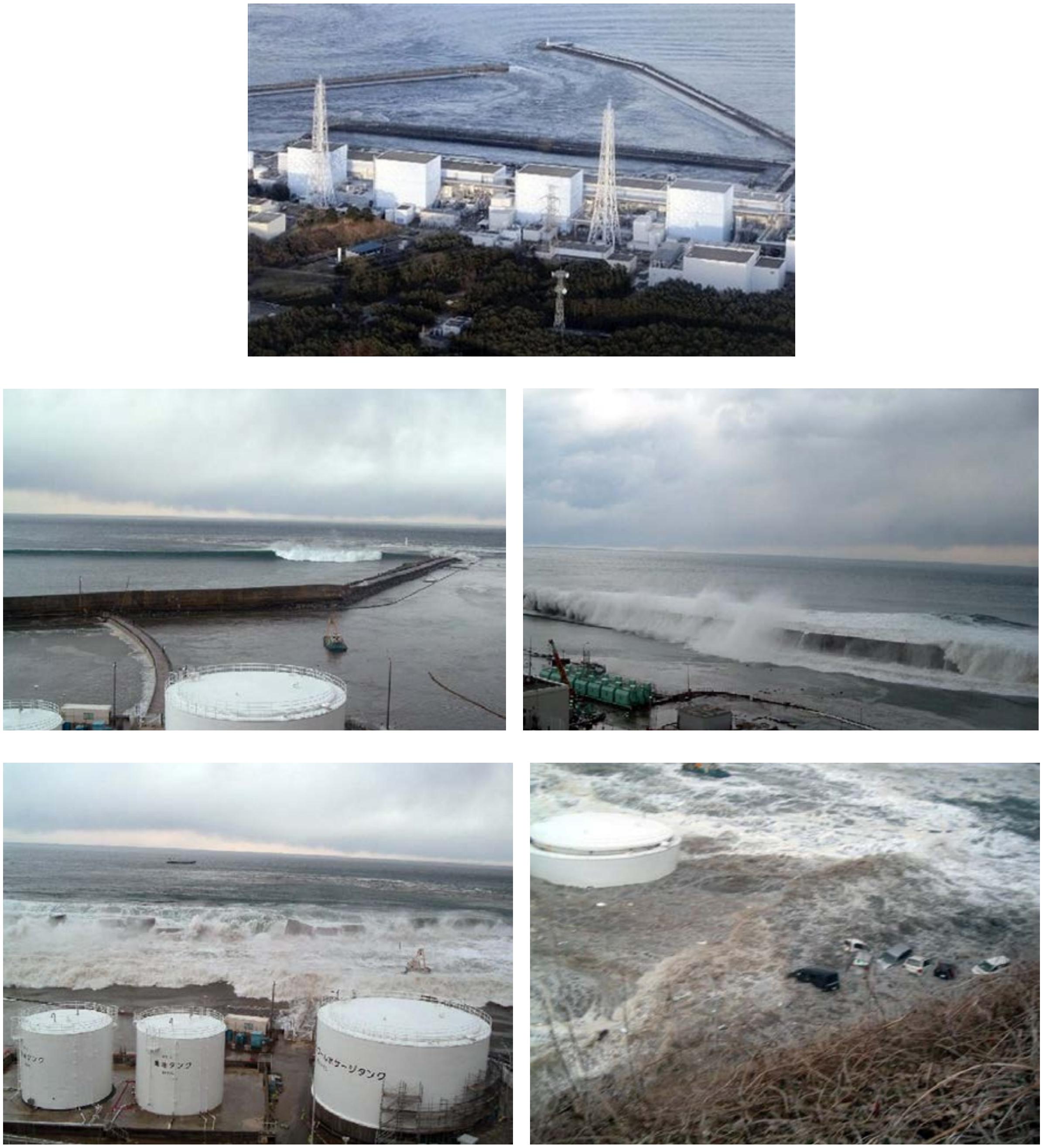


Figure 2. The tsunami wave more than 14 m (46 ft) high that originated 125 miles (200 kms) to the East, impinging on the 6 m protective wall and drowning the Fukushima Daiichi nuclear power plant site, March 11, 2011, Japan. According to the plant design, the maximum probable height of a tsunami at Fukushima was at just 5.7 meters compared with the actual 14 m. The

breakwater wall offered protection against typhoons, but was breached by the tsunami. Source: Tepco.

At the Fukushima Daiichi plant, substantial fuel damage and partial core meltdowns are surmised to have occurred in units 1, 2 and 3 with flooding in the reactors basements from suspected leaks in the piping to the *containment* vessels. Core uncovery occurred in unit 1 at 5 hours after the combined earthquake-tsunami event with the fuel temperature reaching 2,800 ^{o}C at 6 hours into the event. Partial core damage of unit 1 with the formation of a debris bed at the bottom of the core occurred at 16 hours into the accident with its reactor building's basement flooded with 4.2 m of water. The *pressure* vessels of units 2 and 3 are likely to be damaged and leaking water from their bottoms.

The uranium fuel rods of the unit 1 reactor were most badly damaged because it lost its cooling water before the other two reactor units 2 and 3 did. The fuel rods were exposed for several hours before fire trucks could pump in emergency seawater. Tepco assumes that 100 percent of the fuel at Unit 1 has slumped into the outer primary containment vessel. A simulation suggests that the molten fuel corium material was embedded about 70 cms into the concrete base below the pressure vessel. About 190 cms of intact concrete exist between the corium material and the steel vessel. A further 760 cms of concrete stand between the primary concrete and the base mat. At Units 2 and 3, the initial cooling efforts were more successful and a smaller amount of molten fuel corium material is thought to have escaped the pressure vessels and into the primary containment vessels.

Units 4-6 were not operational and were shut-down for maintenance. However, hydrogen produced in the fuel damage of unit 3 flowed through a gas treatment line into unit 4 through damaged valves, leaked through ducts on the 2nd, 3rd and 4th floors and caused a fire and explosion. Hydrogen explosions occurred in the units 1-4. A postulated full core meltdown, in which the molten corium material would melt its way through the pressure vessel and possibly causing a steam explosion was reportedly averted by judicious supplemental cooling.

Effective dose rate levels of 100-200 cSv/hr or rem/hr resulted at the ground level of unit 1. With an occupational maximum allowable effective dose limit of 25 cSv / (person. year) or rem / (person.year) in Japan, this limits the maximum exposure time at these areas to 4-5 hours, hindering the recovery effort and mandating the use of robotic systems.

EARTHQUAKE MAGNITUDE AND STRENGTH

MAGNITUDE SCALE

Referred-to in Japanese as "san ten ichi ichi" or 3/11, the earthquake affected two 50 miles thick tectonic slabs and unleashed an energy of about 480 Mt of TNT equivalent moving the position of part of the coastline 3.6 m to the east. The Nagasaki nuclear device yield was in the range of 20-22 kT of TNT equivalent. The seabed buckled along a 300 km stretch along the fault line involved. An estimated 67 km^3 of ocean water moved towards 860 km of the Japanese coastline with a wave reaching about 24 m in height.

The reported M9.0 magnitude earthquake was more powerful than the design-basis magnitude M8.6 earthquake.

The difference between two Richter scale magnitudes is given by:

$$\Delta M = \log_{10}\frac{M_2}{M_1} = \log_{10} M_2 - \log_{10} M_1 \qquad (1)$$

The ratio of magnitudes can be calculated by using the relation:

$$\begin{aligned} &e^{\ln x} = 10^{\log_{10} x} = x \\ &\frac{M_2}{M_1} = 10^{\log_{10}\frac{M_2}{M_1}} = 10^{\Delta M} \end{aligned} \qquad (2)$$

Since the Richter magnitude scale is a base 10 logarithmic scale, each whole number increase corresponds to a factor of ten increase in the measured amplitude:

$$\Delta M = \log_{10}\frac{10M_1}{M_1} = \log_{10} 10 = 1$$

The difference between the design and experienced earthquakes is a factor of:

$$\frac{M_2}{M_1} = 10^{(9\ 0-8\ 6)} = 10^{0\ 4} = 2.5$$

Mistakenly considering it as a base e logarithmic scale yields an underestimated value of:

$$\frac{M_2}{M_1} = e^{(9\ 0-8\ 6)} = e^{0\ 4} = 2.718^{0\ 4} = 1.4$$

STRENGTH, ENERGY RELEASE, DESTRUCTIVENESS

The magnitude scale compares the measured amplitudes of waves on a seismograph and does not describe the strength described by the energy release from an earthquake. The energy release is what affects structures and causes the actual damage.

To estimate the energy release E, an empirical formula is usually used that relates it to the magnitude M as:

$$\log_{10} E \ \ \alpha_{\ell} \ \ 1.5M \qquad (3)$$

The energy release or strength can be estimated from:

$$\begin{aligned} &10^{\log_{10} E} \ \ \alpha_{\ell} \ \ 10^{1\ 5M} \\ &E \ \ \alpha_{\ell} \ \ 10^{1\ 5M} \end{aligned} \qquad (4)$$

From which:

$$\frac{E_2}{E_1} = \frac{10^{1\,5M_2}}{10^{1\,5M_1}} = 10^{1\,5(M_2 - M_1)} \tag{5}$$

Thus a change of 0.1 in the magnitude M implies:

$$\frac{E_2}{E_1} = 10^{1\,5(0\,1)} = 10^{0\,15} = 1.41$$

or 1.4 times the energy release.

Each whole number increase in the magnitude M corresponds to:

$$\frac{E_2}{E_1} = 10^{1\,5(1)} = 10^{1\,5} = 31.62 \simeq 32$$

times the energy release by the earthquake.

Each increase of 0.2 in the magnitude corresponds to a doubling of the energy release:

$$\frac{E_2}{E_1} = 10^{1\,5(0\,2)} = 10^{0\,3} = 1.995 \simeq 2$$

The ratio between the strengths or energy releases of a 9M and an 8.6M earthquakes can be estimated as:

$$\frac{E_2}{E_1} = \frac{(10^{1\,5})^{9\,0}}{(10^{1\,5})^{8\,6}} = 10^{(1\,5)^{9.0-8.6}} = 10^{(1\,5)^{0.4}} = 10^{1\,176} = 14.99 \simeq 15$$

times the strength and hence the destructiveness.

Large earthquakes have much larger strength or energy release factors than small ones and are hence are much more devastating.

Thus, for Fukushima on a magnitude basis:

$$\frac{M_{actual}}{M_{design-basis}} = 2.5\,,$$

but on a strength, energy release, or destructiveness basis:

$$\frac{E_{actual}}{E_{design-basis}} \simeq 15\,.$$

ACCIDENT PROGRESSION

The situation with cascading failures is unprecedented at two sites and with multiple reactor units simultaneously involved, following a Station Blackout Accident with a loss of offsite and on-site power. Such an event jeopardizes simultaneously both the control and cooling functions of the plant. This situation is characterized as a “beyond-design-basis accident.”

The earthquake triggered a shutdown of the three operating reactors at the site as designed. The three others were already shut down for maintenance. There were 6,415 people at the site of which 5,500 were subcontractors.

The earthquake put out of service a transformer station about 10 kms from the plant cutting out the site connection to the electrical grid system. Because of this situation, even though the grid system was restored within 50 minutes from the earthquake, offsite power was still not available to the plant.

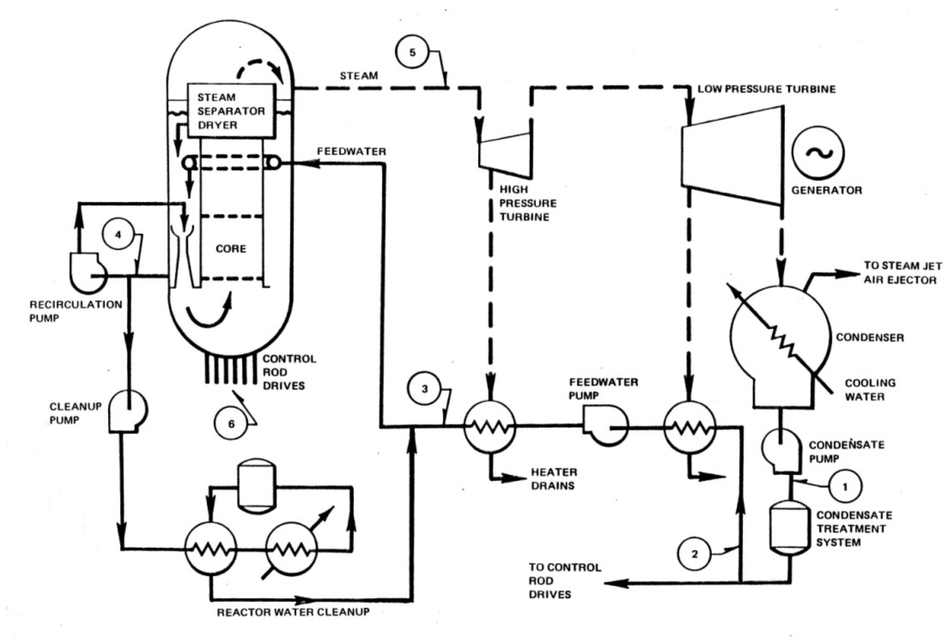


Figure 3. Typical BWR flow diagram. The role of the core spray system in the progression of the accident is undetermined. Source: GE.

Figure 4. BWR primary coolant recirculation pump. Source: Tepco.

Figure 5. Fukushima Daiichi Tsunami water ingress and egress, drowning plant components at the base of the ventilation stack system, March 11, 2011. Source: Tepco.

EMERGENCY CORE COOLING SYSTEM, ECCS

Because of the successful shut-down of the reactor as a result of the earthquake, the turbines were also tripped as the main steam isolation valves shut down the steam supply to the turbines. Accordingly, the main turbines become unavailable for electrical power generation that is usable by the plant systems as well as their associated instrumentation.

With the loss of onsite as well of offsite power another line of defense was in the Emergency Core Cooling System, ECCS. Power could still be provided to the plant by 13 emergency diesel generators inside and outside the plant enclosure, each capable with its fuel supply of delivering 6 MWhr of energy. Eight of these diesel generators, each the size of a locomotive, were located in the basement number 1 of the turbine hall. The turbine halls lie about 140 m from the seashore. Two other diesel generators were on the ground floor behind unit 4 which was shutdown for maintenance, and 3 others were inside and outside the enclosure of unit 6 which was also offline for servicing.

Upon the impact of the tsunami wave about 15 minutes after the earthquake wave, it crashed over a 2.5 km breakwater consisting of 60,000 concrete blocks and 25 tons tetrapods, as well as a 5.6 m height wall on the seabed facing the site. The plant was built on solid rock ground 10 meters above sea level.

In spite of these defenses, which would have been able to withstand the effects of a major hurricane, a 15 m high wave flooded parts of the plant in 6 meters of water before retreating back to the ocean. The sea water intake structures for the normal and emergency service water were apparently affected, possibly through silting.

The most notable effect was the flooding of the below-grade parts of the plant particularly in the basements of the turbine halls as well as other buildings. The water level reached about 1.5 m in one turbine building. This disabled 12 of 13 emergence diesel generators and destroyed their associated electrical switching gear as the sea water shorted the electrical circuits.

Within an hour after the quake that started at 2:46 pm, at 3:41 pm all onsite power from the diesel generators had failed, plunging the plant into a full-fledged “station blackout.”

EMERGENCY BATTERY POWER

Banks of charged electrical “coping batteries” were still available, and were deployed to provide emergency cooling. These could deliver power for about 12 hours until external or onsite power could be restored to the plant.

The monitoring equipment failed, probably as a result of the electrical circuits malfunction denying the operators information about the plant status.

At 4:36 pm, within 2 hours from the earthquake, the Tepco utility acknowledged the situation and 9 minutes later notified the responsible authorities.

At 7:03 pm, a “nuclear emergency” was declared prompting the evacuation of the nearby population, which was expanded to a radius of 20 kms within 24 hours later.

RESIDUAL HEAT REMOVAL SYSTEM, RHR

The earthquake initiated an automatic shutdown of the plants by insertion of the control rods into the coreas designed.

Nuclear power plants differ from other heat engines in that after shutting down the chain reaction, the fission products resulting from the fissile elements in the core continue emitting both gamma and beta particles radiation that decreases at an exponential rate.

This “residual heat,” “decay heat,” “after heat,” or “afterglow heat,” needs to be extracted and rejected until it has decayed within days to weeks to a level that does not need active cooling anymore.

Under normal conditions, the excess heat in a BWR is rejected by bleeding steam from the steam lines and is quenched in the main condenser in the turbine part of the plant.

After shutdown or during servicing and maintenance procedures, a Residual Heat Removal System, RHR is also incorporated in the design of nuclear power plants for this purpose. Residual heat pumps and heat exchangers are used until such time when its heat generation is comparable to the heat generated by pumping the water. At such time the RHR pumps can be switched off.

The RHR usually consists of 4 pumps, 2 heat exchangers and their associated piping, valves and instrumentation.

A mode of RHE operation allows the removal of heat from the primary containment following a Loss of Coolant Accident, LOCA. Another operational mode is as a Low Pressure Coolant Injection, LPCI system after the reactor has been depressurized in a postulated LOCA.

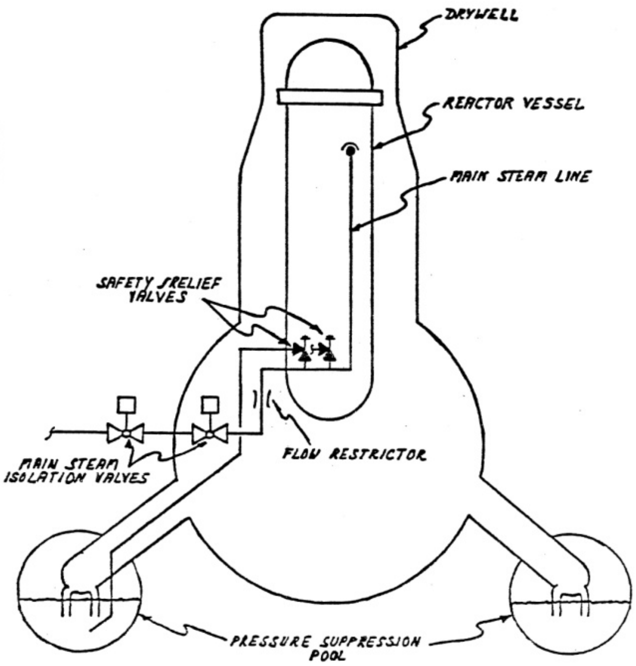


Figure 6. Main isolation valves and safety relief valves used in depressurization of the BWR. Source: GE.

LOSS OF REACTOR CORE ISOLATION COOLING SYSTEM, RCIC

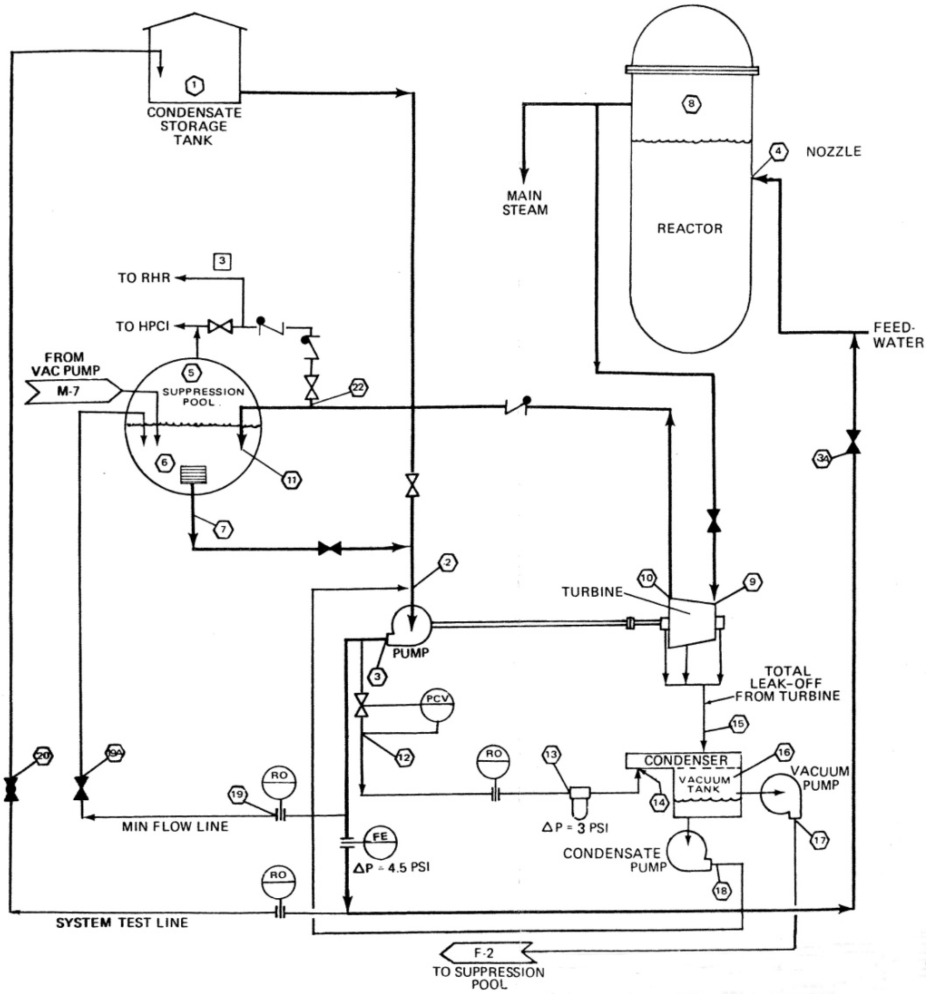


Figure 7. BWR Reactor Core Isolation Cooling system, RCIC. A steam turbine uses steam to drive a pump injecting water drawn from the condensate storage tank into the core. Exhaust from the steam turbine is directed to the pressure suppression pool. HPCI: High Pressure Coolant Injection system, RHR: Residual Heat Removal system.

Failure of the reactor cooling function carried out by the Reactor Core Isolation Cooling, RCIC system occurred in units 1, 2 and 3 at the Fukushima Daiichi site and at unit 4 at the Fukushima Daiini site; a situation stipulated in article 15, clause 1 of the “Act on Special Measures Concerning Nuclear Emergency Preparedness” in Japan.

The RCIC provides makeup water to the core during a reactor shutdown if the feedwater flow is not available. It is started automatically upon receipt of a “low water” reactor water level signal or manually by the reactor operator.

Cooling water is pumped to the core by a turbine driven pump using steam from the reactor system. It normally takes its suction from the condensate storage tank through a common line to the High Pressure Coolant Injection, HPCI pump suction. The RCIC can also pump water from the pressure suppression pool.

NUCLEAR PRESSURE RELIEF SYSTEM

The nuclear pressure relief system protects the Coolant Pressure Boundary, RPCB against damage due to overpressure. Pressure operated main Safety Relief Valves, SRVs are available to discharge steam from the Nuclear Steam Supply System, NSSS to the pressure suppression pool.

Part of it is the Automatic Depressurization System, ADS which depressurizes the NSSS in the case of a LOCA in which the High Pressure Injection System, HPCI fails to maintain Reactor Pressure Vessel, RPV water level. The HPCI pumps generate a high head and consequently a low flow rate.

The depressurization of the NSSS allows the initiation of the operation of the LPCI system with a low head but large flow rate to adequately cool the fuel.

MAIN STEAM ISOLATION VALVES, MSIVs

The main steam system in the BWR operates during stable and transient conditions to:

1. Receive the generated steam in the core and convey it to the turbine for electrical power generation,
2. Bypass any excess steam above what is needed by the turbine and its auxiliaries to the condenser.

Main steam line flow restrictors of the venture type exist in each steam line inside the primary containment. They limit the loss of coolant resulting from a main steam line break outside the primary containment. The coolant loss is limited so that the reactor vessel water level remains above the top of the core during the time required for the Main Steam-line Isolation Valves, MSIVs to close to protect the fuel barrier.

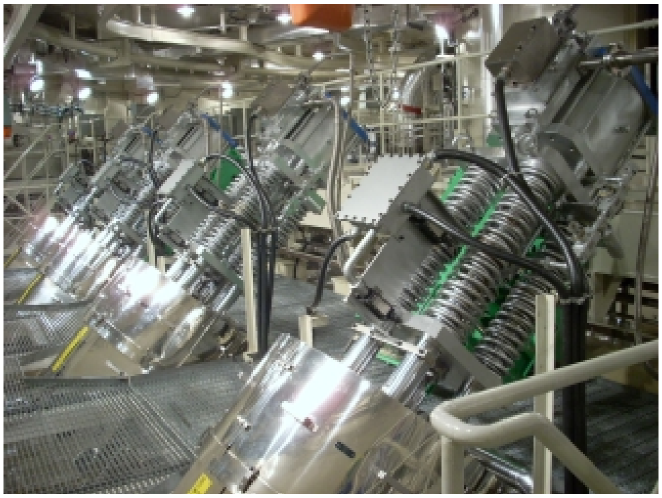


Figure 8. BWR Main Steam Isolation Valves, MSIVs. Source: Tepco.

Usually 3 MSIVs are installed on each main steam line. These consist of two MSIVs, one located inside, and the other outside of the primary containment, and a Main Steam Stop Valve, MSSV that is located downstream from of the outboard MSIV as a long term isolation valve.

The part of the main steam line supply system between the outboard MSIV and the MSSV are designed to assist in eliminating air leakage from the MSIVs after a postulated accident.

In case a main steam line break occurs inside the containment, closure of the isolation valve inside or outside the primary containment acts to seal the primary containment itself.

The primary MSIVs automatically close to isolate the Reactor Coolant Pressure Boundary, RCPB in the event of a pipe break downstream of the outboard isolation valve. This procedure limits the loss of coolant and the possible release of radioactive material from the NSSS.

DEPRESSURIZATION, STEAM VENTING

As no circulation of the core was provided the water turned into steam uncovering the core. In some BWRs a core spray system would spray the fuel assemblies to cool them. Steam was generated at an increasing rate raising the system's pressure. The safety relief valves vented the steam into the pressure suppression pool, quenching and condensing it.

In the process of venting steam to reduce the pressure in the containment system, a stipulated hydrogen explosion was reported at the Fukushima unit 1 on March 13, 2011 at the Daiichi site with associated fuel damage, containment structure damage, partial core meltdown and fission products release. Small amounts of radioactivity were vented, the reactor had 400 fuel assemblies loaded in its core, and the storage fuel pool had 292. The rubble from the roof covered the reactor's loading deck and fell into the fuel storage pool.

If the core gets uncovered, the zirconium cladding interacts with the hot steam releasing hydrogen; a non-condensible gas. Under normal conditions, the steam and hydrogen gas are directed to the filtered ventilation system and ventilated from the exhaust stack and released at an elevated location. Hydrogen recombiners exist at most BWRs burning the hydrogen in a controlled manner by sparging it above water.

Because of the Station Blackout situation, the exhaust system and the hydrogen recombiners may not have been operational, and the steam and hydrogen accumulated inside the secondary containment structure.

Hydrogen is combustible at concentrations in the air above 4 percent, and reacts explosively with oxygen above a concentration of 8 percent. A spark or auto-ignition can initiate the process.

An explosion was reported in unit 2 on March 15, 2011 possibly damaging its pressure suppression pool. Fuel damage and a partial core meltdown is presumed with some fission products vented. The reactor' core had 548 fuel assemblies and the storage fuel pool had 587.

Some unsubstantiated reports suggested that the hydrogen explosion originated in the turbine building in the hydrogen used to cool the generators' stator.

A more energetic presumed hydrogen explosion associated with steam depressurization followed at the unit 3 on March 14, 2011 with a fire and may have lead to reactor vessel and pressure suppression pool damage. This unit uses a Mixed Oxide, MOX fuel mixture of UO_2 and PuO_2 which raised concern because of a lower melting point of Pu than U, as well as the combined chemical and radio-toxicity of Pu. The reactor core had 548 fuel assemblies and the storage fuel pool had 587 assemblies. The reactor containment vessel may have been damaged and spent fuel may have been uncovered. A suspected "long vertical crack" running down the side of the containment vessel was reported by a utility official. There is also a suspicion of molten corium material leaking onto the concrete base mat and interacting with it. The powerful explosion may have ejected components at the top of the reactor including concrete shield plugs and parts of a loading crane.

At 6 pm, March 15, 2011 a possible hydrogen explosion occurred within the previously shut-down unit 4, which under an outage condition, had the fuel from its core transferred to its storage fuel pool. The pool is reported to contain 1,331 fuel assemblies of which 548 were removed from the core for maintenance considerations.

Hydrogen produced in the fuel damage of unit 3 flowed through a gas treatment line into unit 4 through damaged valves, leaked through ducts on the 2nd, 3rd and 4th floors and caused a fire and explosion. Hydrogen explosions occurred in the units 1-4.A fire at the unit 4 lasted for two hours and was extinguished at 2:00 pm on March 15, 2011 and reignited on March 16, 2011, then extinguished again.

Units 5 and 6 were already shutdown when the earthquake and tsunami affected the reactors buildings. Cooling in the storage fuel pools became a concern. Unit 5 had 548 fuel assemblies in the core and 946 in the storage fuel pool. Unit 6 had 764 fuel assemblies in the core and 876 in the storage fuel pool.

There were reports that a seismically hardened separate building was used for fuel storage with temporary holding in the pool in the reactor building.

A hydrogen explosion is stipulated at another site at unit 4 of the Fukushima-Daini plant that was reported to have access to offsite power from the electrical grid and hence recovered as designed from the combined earthquake and tsunami event.

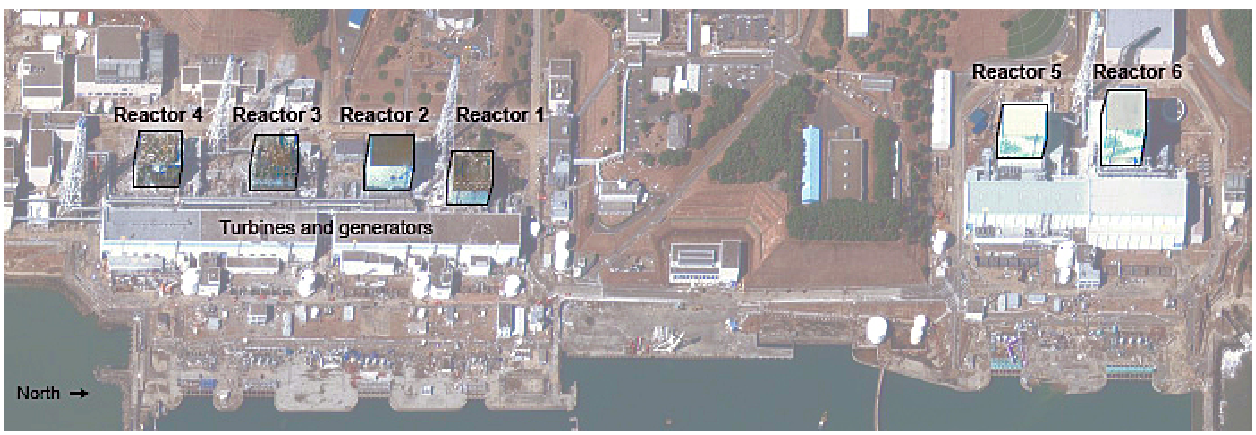


Figure 9. Fukushima Daiichi units 1-6. Source: GeoEye, Digital Globe.

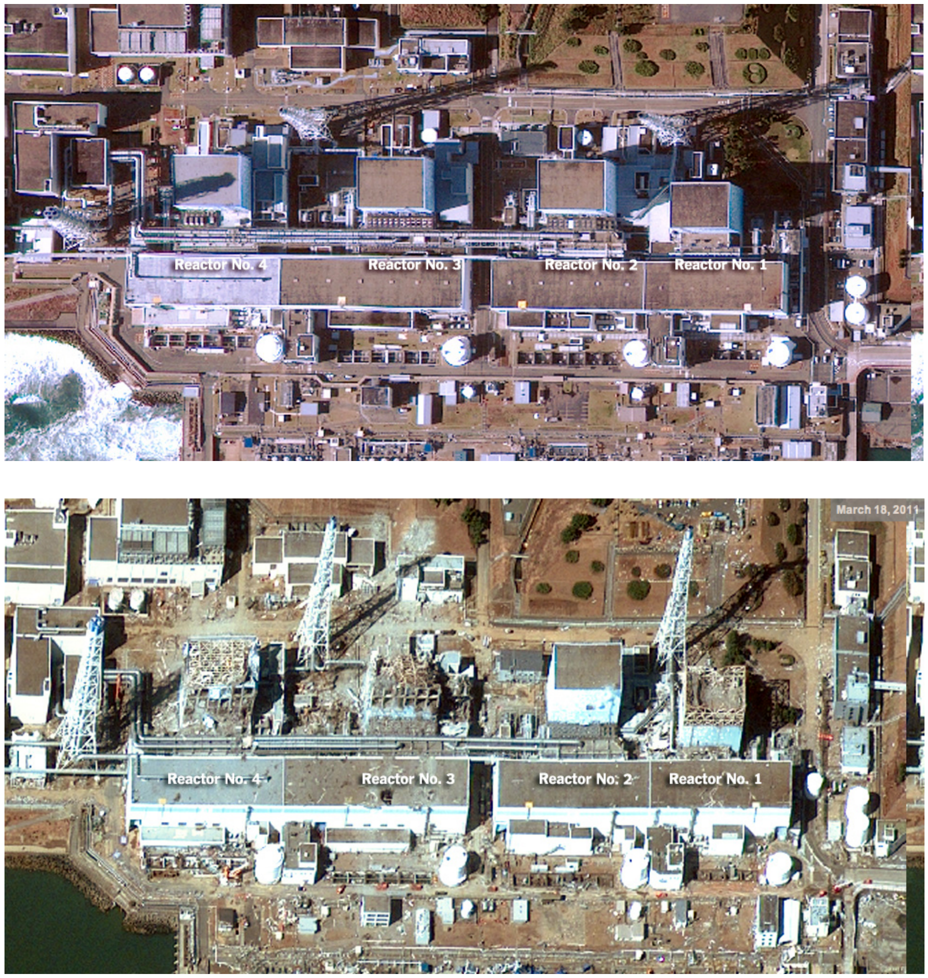


Figure 10. Fukushima Daiichi units 1-4 before and after the earthquake and tsunami event. Steam can be seen venting from the reactor unit 2 on March 27, 2011. Source: Digital Globe.

Figure 11. Remnants of a hydrogen explosion in Fukushima unit 1 (far left) exposing reactor loading deck and burying it under concrete rubble. Fire and a hydrogen explosion associated with steam depressurization and fuel damage occurred in unit 3. Fire starting at side of building in unit 4 may have originated from hydrogen generated in unit 3 that was piped into the shut-down unit 4, on March 15, 2001. Photo: DigitalGlobe.

A population evacuation and a rolling power blackout have been implemented. A skeleton crew of 70-250 volunteer plant personnel managed the cooling of the damaged reactors. The fuel storage pools became at risk of losing their cooling water and become subject to fuel damage.

DEBRIS BED FORMATION AND COOLING

Based on the assumption that the fuel assemblies and the control rods still retained their integrity, cooling with sea water, mixed with boron as a neutron absorber to prevent criticality, helped reduce further damage. Later on, fresh water was hauled in barges to the reactor site.

However, if the fuel and the control rods were already fully damaged and forming a debris bed, alternate cooling approaches can be considered. Porous non-neutron moderating materials such as sand or gravel or iron pebbles to reduce neutron moderation and prevent criticality in the formed debris bed could be attempted, in addition to using boron or lithium dissolved in water as a neutron absorber. The observed rising steam plume from the Fukushima unit 3 implied the possibility of the existence of a debris bed being cooled by the evaporating water as steam.

Figure 12. Military helicopters dumping water into fuel storage pools on March 17, 2011, were ineffective because of high winds. They were replaced by water cannons from fire trucks on March 18, 2011 to extinguish fires and add water to the fuel storage pools. Source: Japan Self Defense Forces.

Figure 13. Station Blackout loss of power to the control room of the Fukushima Daiichi unit 1 reactor on March 24, 2011. Restoring offsite power to units 1 and 2 and power to the control room of unit 2 on March 26, 2011. The hanging ceiling tiles resulted from the earthquake. Source: Tepco.

PREVIOUS EARTHQUAKE EVENTS

Nuclear power plants are designed to withstand the maximum magnitude earthquake on the Richter scale at their location. The Fukushima plant is reportedly designed to withstand an 8.6M earthquake on the Richter scale, whereas it was subject to an 8.9-9.0M one.

The 2004 Sumatra earthquake and tsunami lead to the shutdown of the Kalpakkam nuclear plant near Chennai in India and four plants in Taiwan.

Japan’s worst earthquake was a magnitude 8.3M one at Kanto in 1923 causing 143,000 deaths. Another 7.2M one at Kobe in 1995 killed 6,400 people. Japan lies near the Pacific Ring of Fire seismically active zone where 90 percent of the world’s earthquakes occur. A December 26, 2004 at Sumatra, Indonesia, earthquake and tsunami caused the death of 230,000 people and affected 12 countries. On February 2010, a magnitude 8.8M earthquake in central Chile caused a tsunami that killed 524 persons.

The earthquake event was the most powerful in Japan’s recorded history, and the fifth in the world. Japan’s main island was shifted 8 feet or 2.5 meters as a result of the seismic movement, and the Earth’s axis was shifted by 10 cms or 2.5 inches.

The fission chain reactions in the BWR reactors, as designed, were successfully shut down through the successful insertion of the control rods by the automatic control system, but the decay heat removal system did not operate as designed to extract the fission products decay heat from the system leading to a loss of cooling accident. The electrical components of the Emergency Core Cooling System, ECCS diesel generators at the plant were reportedly affected by flooding by the tsunami, causing their shutdown by affecting their switchgear component in the flooded lower parts in the plant.

Figure 14. Earthquake-caused ground subsistence around light oil storage tank of 30,000-40,000 gallons capacity, 1979. Source: Tepco.

Figure 15. Earthquake-caused displacement of connecting duct to the main ventilation stack, 1979. Source: Tepco.

On June 17, 2010, the Fukushima unit 2 BWR was scrammed due to a generator problem. Power was lost for a short period because the switch-over to the offsite power supply was not successful. The feedwater pump stopped and the water level in the reactor fell about 2 meters. The emergency diesel generators were successfully started. The ECCS did not need to be activated as the core water level was restored by the Core Isolation Cooling System, CICS steam-driven pump.

The combined earthquake and tsunami event caused a loss of power at the plant. If power from both offsite and onsite sources is unavailable, the event is designated as a “Station Blackout Accident.” This has resulted in a Loss of Coolant Accident, LOCA with fuel damage and radiation leakage similar to the Three Mile Island occurrence. Radiation levels rose to 10^3 times normal level at the control room of unit 1 and to 8 times normal background level outside the facility as a result of fuel damage and fission products release. Cooling was jeopardized at two other units at the 6-unit plant at the Fukushima Daiichi site. The cooling ability was apparently also jeopardized at a nearby Fukushima Daiini site which retained its offsite power supply and was able to recover according to design.

The Fukushima nuclear power plant’s emergency diesel generators could not be used because of reported damage to the plant electrical systems caused by the subsequent tsunami. To provide power to cool the reactors, emergency generators and fire trucks were brought in by the electrical utility Tokyo Electric Power Company to the site of the reactors.

Figure 16. Fukushima Daiichi Boiling Water Reactors, BWRs nuclear Power plant, at Okumamachi, Fukushima Prefecture, Japan. The reactors are cooled with ocean water and are situated 148 miles or 238 km northeast of Tokyo. Connection to the grid shows up at the upper left side. Source: AP.

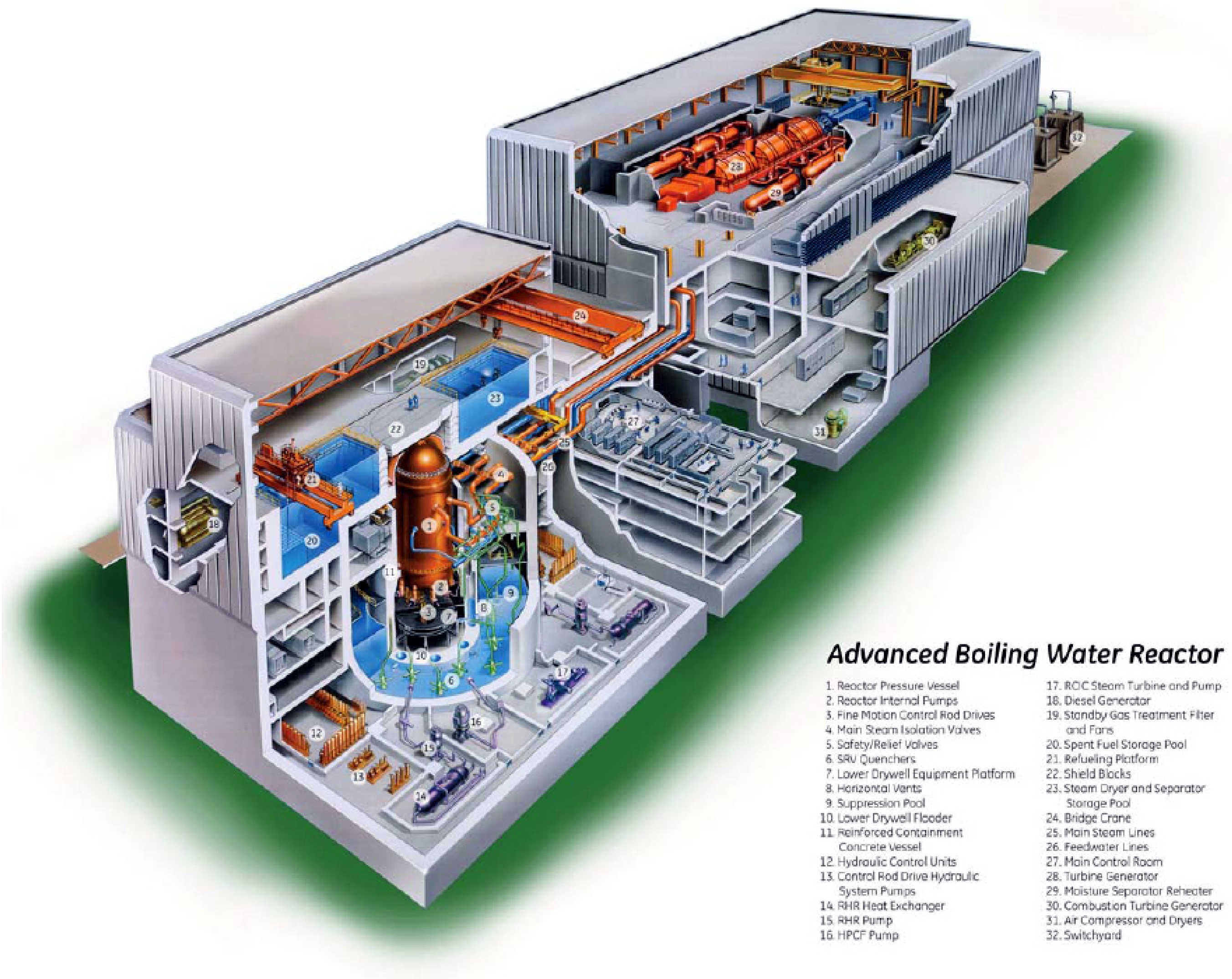


Figure 17. Plant layout of the Advanced Boiling Water Reactor, ABWR design identifies the diesel generator (18) as located high up at the level of loading deck inside the reactor building (upper left). The transformers in the switchyard (33), which were misidentified from satellite photographs as the diesel generators, are outside the building enclosure and could have been affected by the tsunami. The most significant vulnerability to the tsunami is the flooding of the lower level of the plant that would have impacted the functioning of the electrical components as well as the Residual Heat Removal, RHR pump (15), the HPCF pump (16), and the Reactor Core Isolation Cooling RCIC system steam turbine and pump (17). Source: GE.

Figure 18. Transformer fire caused by 1979 earthquake. Notice the location of the transformer outside the plant enclosure and its vulnerability to water-flooding from the tsunami event. Source: Tepco.

Concurrently, a fire broke out in a transformer and was extinguished at the Tohoku Electricity Company's Onagawa nuclear plant in northeast Japan as a consequence of the earthquake. A reactor at the Onagawa site experienced a coolant leak.

Eleven nuclear power plants closest to the epicenter were safely shut down out of a total of 55 reactors, representing 20 percent of the total nuclear installed electrical capacity in Japan. The grid connections were restored within 50 minutes of the earthquake, but not the one to the Fukushima Daiichi plant

STATION BLACKOUT ACCIDENT

OVERVIEW

At about 2:46 pm local time on Friday, March 11, 2011, units 1, 2 and 3 of the six reactors at the Fukushima Daichi site automatically shut down following the seismic wave from the Tohoku-Chihou-Taiheiyo-Oki earthquake. Units 1, 2 and 6 are GE Boiling Water Reactors, BWRs. The other units are Toshiba and Hitachi BWRs. Unit 1 started operation in 1971. Pressure increased to 1.5-2 times the operational pressure implying steam formation from insufficient cooling circulation at one of the reactors.

Unit 1 has a rated power of 460 MWe, and units 2 and 3 have rated powers of 784 MWe each. Unit 1 was slated to shut down for maintenance.

The reactors remains affected by a loss of offsite power caused by the damage by the earthquake of a transformer station about 10 kms from the plant. If these other power systems failures were caused by both the earthquake and tsunami, this can be classified as a common-mode failure.

The Tokyo Electric Power Company, Tepco utility operates 17 BWR reactor units at 3 reactor complexes.

Table 1. Description of reactors operated by Tepco.

Unit	Manufacturer,	Rated Power,	Commercial	Containment	Fuel

	reactor model	MWe	operation date	design	loading [tons U]
Fukushima-Daiichi 1	GE, BWR-3	460	March 26, 1971	Mark I	69
Fukushima-Daiichi 2	GE, Toshiba BWR-4	784	July 18, 1974	Mark I	94
Fukushima-Daiichi 3	Toshiba, BWR-4	784	March 27,1976	Mark I	94
Fukushima-Daiichi 4	Hitachi, BWR-4	784	October 12, 1978	Mark I	94
Fukushima-Daiichi 5	Toshiba, BWR-4	784	April 18, 1978	Mark I	94
Fukushima-Daiichi 6	GE, Toshiba, BWR-5	1,100	October 24, 1979	Mark II	132
Fukushima-Daini 1	Toshiba, BWR-5	1,100	April 20, 1982	Mark II	132
Fukushima-Daini 2	Hitachi, BWR-5	1,100	February 3, 1984	Mark II Advanced	132
Fukushima-Daini 3	Toshiba, BWR-5	1,100	June 21, 1985	Mark II Advanced	132
Fukushima-Daini 4	Hitachi, BWR-5	1,100	August 25, 1985	Mark II Advanced	132
Kashiwazaki Kariwa 1	Toshiba	1,100	September 18, 1985	Mark II	132
Kashiwazaki Kariwa 2	Hitachi	1,100	September 28, 1990	Mark II Advamced	132
Kashiwazaki Kariwa 3	Toshiba	1,100	August 11, 1993	Mark II Advanced	132
Kashiwazaki Kariwa 4	Hitachi	1,100	August 11, 1994	Mark II Advanced	132
Kashiwazaki Kariwa 5	Hitachi	1,100	April 10, 1990	Mark II Advanced	132
Kashiwazaki Kariwa 6	Toshiba-Hitachi-GE, ABWR	1,356	November 7, 1996	Reinforced concrete	872
Kashiwazaki Kariwa 7	Hitachi-Toshiba-GE, ABWR	1,356	July 2, 1997	Reinforced concrete	872

Table 2. Fuel loadings at the Fukushima Daiichi site.

Unit	Number of fuel assemblies, reactor core	Fuel loading in core [tons U]	Number of fuel assemblies, spent fuel storage pool	Fuel loading,spent fuel storage pool [tons U]
Fukushima-Daiichi 1	400	69	292	50

Fukushima-Daiichi 2	548	94	587	100
Fukushima-Daiichi 3	548 (MOX: 32)	94	514	90
Fukushima-Daiichi 4	548	94	783	130
Fukushima-Daiichi 5	548	94	946	160
Fukushima-Daiichi 6	764	132	867	150

DECAY HEAT REMOVAL

Upon shutdown of the fission power generation by the control rods, decay heat continued to be generated to an initial level of about 3 percent of the fission power at one minute after shutdown. It decreases exponentially as a function of time but must continue to be cooled over a few days period by the Residual Heat Removal, RHR system.

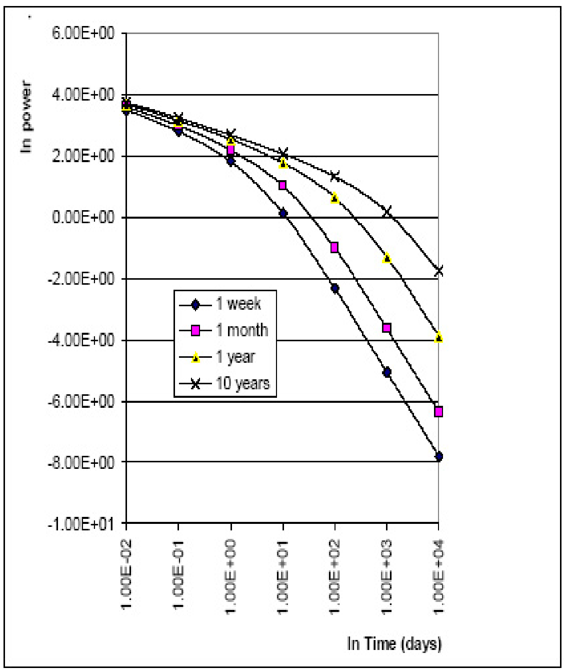


Figure 19. Decay heat power release for a 3,000 MWth Light Water Reactor, LWR for different operational times. The decay heat generation power decreases rapidly within a few days after shutdown.

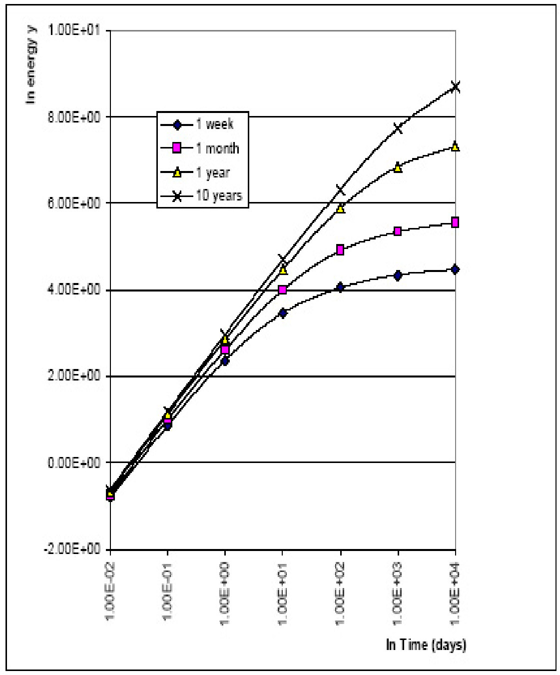


Figure 20. Decay energy or integrated power release after shutdown for a 3,000 MWth LWR for different reactor operational times. If not extracted and rejected, the energy released would result in fuel damage including fission products release and hydrogen generation.

The decay heat power ratio is given by:

$$\frac{P[MWth]}{P_0[MWth]} = 6.48x10^{-3} P_0[t^{-0\,2} - (t + T_0)^{-0\,2}] \qquad (6)$$

where : P_0 is reactor thermal fission power before shutdown, MWth,

P is thermal decay heat power generation, MWth,

t is time after shutdow, days,

T_0 is the time of operation of the reactor at the power level P_0, days.

At 1 second or immediately after shutdown, the decay power ratio would be for a reactor that operated for a period of T_0 = 1 year = 365 days:

$$\frac{P(t)}{P_0} = 6.48 \times 10^{-3}[t^{-0\,2} - (t+T_0)^{-0\,2}]$$
$$= 6.48 \times 10^{-3}[(\frac{1}{24 \times 60 \times 60})^{-0\,2} - (\frac{1}{24 \times 60 \times 60} + 365)^{-0\,2}]$$
$$= 6.48 \times 10^{-3}[(0.00001157)^{-0\,2} - (365.00001157)^{-0\,2}]$$
$$= 6.48 \times 10^{-3}[9.71187 - 0.30728]$$
$$= 6.48 \times 10^{-3} \times 9.40459$$
$$= 60.94 \times 10^{-3}$$
$$= 0.06094$$
$$\approx 6\%$$

Within just 1 minute after shutdown for a reactor that operated for one year the decay power ratio would be for a reactor that operated for a period of T_0= 1 year = 365 days:

$$\frac{P(t)}{P_0} = 6.48 \times 10^{-3}[t^{-0\,2} - (t+T_0)^{-0\,2}]$$
$$= 6.48 \times 10^{-3}[(\frac{1}{24 \times 60})^{-0\,2} - (\frac{1}{24 \times 60} + 365)^{-0\,2}]$$
$$= 6.48 \times 10^{-3}[(0.000694)^{-0\,2} - (365.000694)^{-0\,2}]$$
$$= 6.48 \times 10^{-3}[4.28280 - 0.30728]$$
$$= 6.48 \times 10^{-3} \times 4.52072$$
$$= 29.29 \times 10^{-3}$$
$$= 0.02929$$
$$\approx 3\%$$

Assuming a plant thermal efficiency of 1/3, the thermal power of unit 1 would be 460 / (1/3) = 460 x 3= 1,380 MWth.

Initially, at one second or immediately after shutdown, thus 1,380 x (6/100) = 82.8 MWth of thermal power cooling has to be provided.

At one minute after shutdown it rapidly decreases to ½ the initial amount to: 1,380 x (3/100) = 41.4 MWth of thermal power cooling that has to be provided.

If cooling is successful for 24 hours or 1 day after shutdown, the amount of required cooling reduces dramatically to:

$$\frac{P(t)}{P_0} = 6.48\times 10^{-3}[t^{-0.2} - (t+T_0)^{-0.2}]$$
$$= 6.48\times 10^{-3}[(1)^{-0.2} - (1+365)^{-0.2}]$$
$$= 6.48\times 10^{-3}[1-(366)^{-0.2}]$$
$$= 6.48\times 10^{-3}[1-0.3071]$$
$$= 6.48\times 10^{-3}\times 0.6929$$
$$= 4.49\times 10^{-3}$$
$$= 0.00449$$
$$\approx 0.45\%$$

The amount of required cooling 1 day after shutdown is now 1,380 x (0.45/100) = 6.21 MWth

If cooling is successful for 1 week or 7 days after shutdown, the amount of required cooling reduces dramatically to:

$$\frac{P(t)}{P_0} = 6.48\times 10^{-3}[t^{-0.2} - (t+T_0)^{-0.2}]$$
$$= 6.48\times 10^{-3}[(7)^{-0.2} - (7+365)^{-0.2}]$$
$$= 6.48\times 10^{-3}[0.6776-(372)^{-0.2}]$$
$$= 6.48\times 10^{-3}[0.6776-0.3061]$$
$$= 6.48\times 10^{-3}\times 0.3715$$
$$= 2.407\times 10^{-3}$$
$$= 0.0024$$
$$\approx 0.24\%$$

The amount of required cooling 1 week after shutdown is now just 1,380 x (0.24/100) = 3.31 MWth

BWR ENGINEERED SAFETY FEATURES, ESFs

The Reactor Core Isolation Cooling, RCIC system’s steam-driven turbine provides enough coolant drawn from the Condensate Storage Tank to make up for coolant losses as steam from the safety relief valves on the steam headers to reduce the system’s increase in pressure. The Automatic Depressurization System, APS, does not require operator’s action, even though it can be overridden by the operators.

The loss of offsite power was reported to have triggered the emergency diesel generators to provide backup power for the plant cooling and control systems.

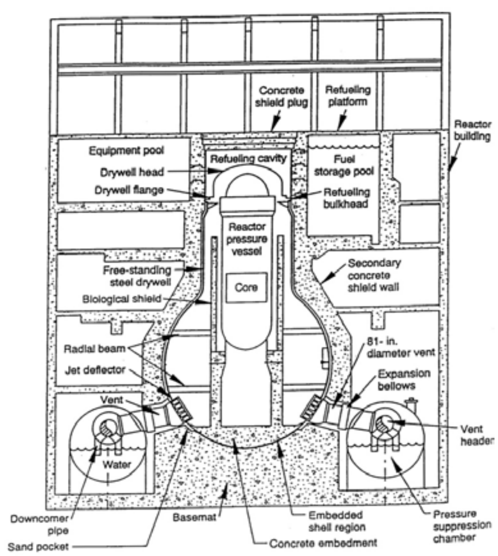
At 3:41 pm, about an hour after the plant was shut down, the emergency diesel generators stopped, leaving the reactor units 1 and 2 and 3 with no AC power for important cooling functions. The Japanese army hauled diesel generators to the site.

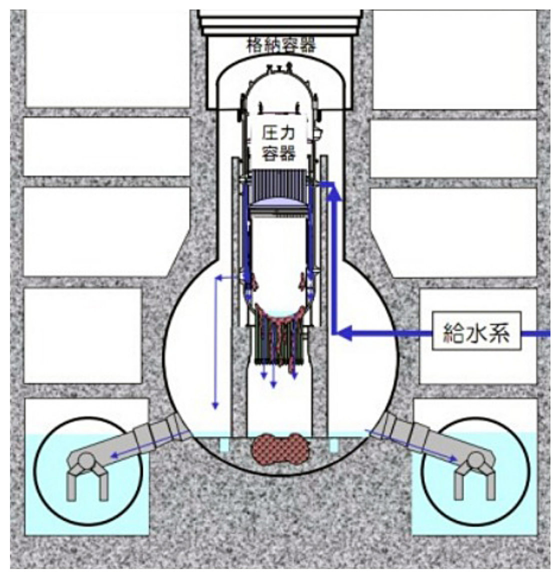
The failure of the diesel generators is correlated by the utility company Tepco with the arrival of the tsunami wave that caused flooding in the area. The focus of the earthquake was about 240 km from the coast, and it would have taken it about 15-60 min to reach the plant site.

With the loss of both offsite and onsite power, the accident is classified as a “Station Blackout Accident.” Nuclear power plants use DC and AC power to operate electrical motors, valves and instrumentation. The loss of both offsite and onsite AC power makes the control and monitoring functions inoperable. If the cooling is not restored, the coolant in the core eventually boils off, oxidizing the fuel cladding and releasing the volatile fission products. If the control rods were not inserted, the coolant evaporation and the ensuing loss of neutron moderation would shut down the fission power generation, but not the decay heat generation.

BWRs use a steam-driven Reactor Core Isolation Cooling, RCIC system which can be operated without AC power and does not require electrical pumps. However such a system needs DC power provided by batteries to operate instrumentation, valves and controls.

If the batteries charge is depleted within 9-12 hours before DC and AC power are restored, the RCIC cannot continue supplying cooling to the reactor core in the form of coolant circulation, the reactor internal core spray system, and the decay heat removal system.





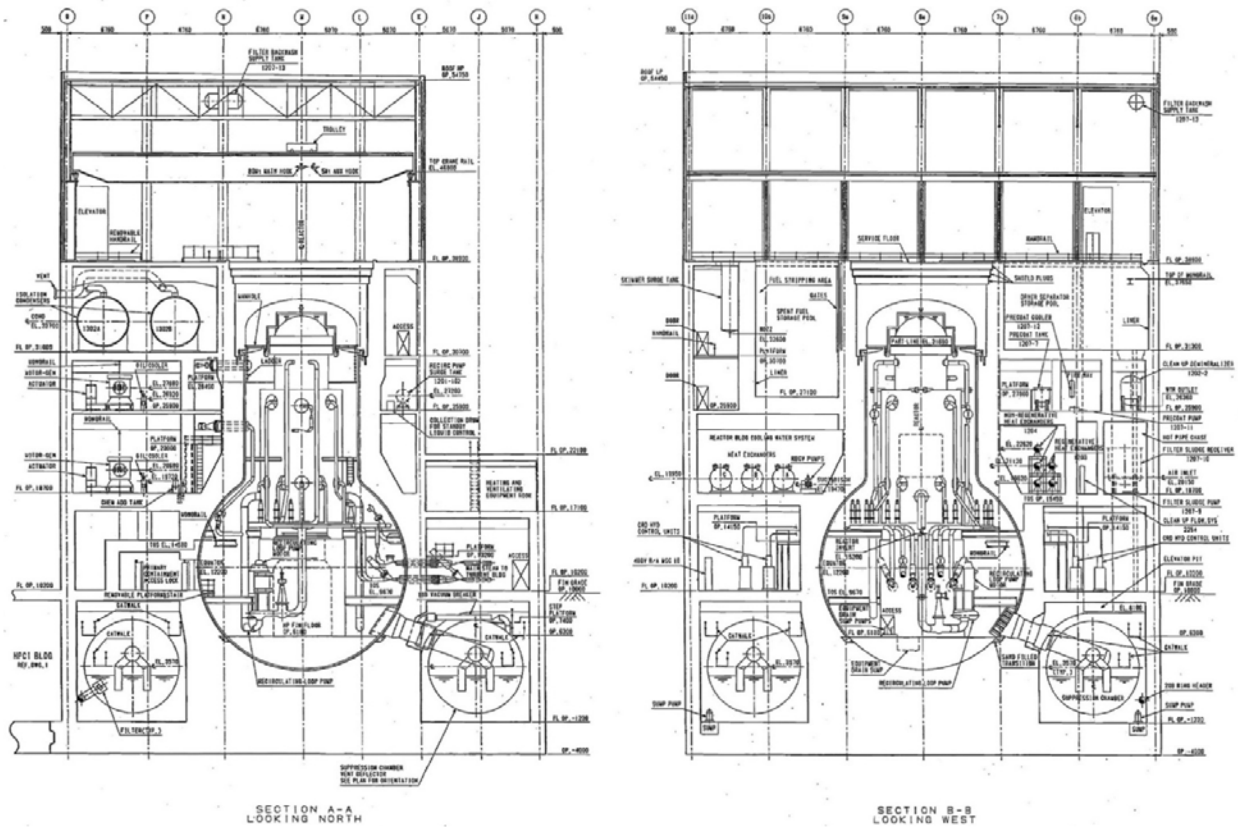


Figure 21. BWR Mark I, light bulb design showing the toroidal steel pressure suppression pool, and the gate between fuel storage pool and reactor top. Source: GE, Japan Ministry of Economy, Trade and Industry, METI, Tepco.

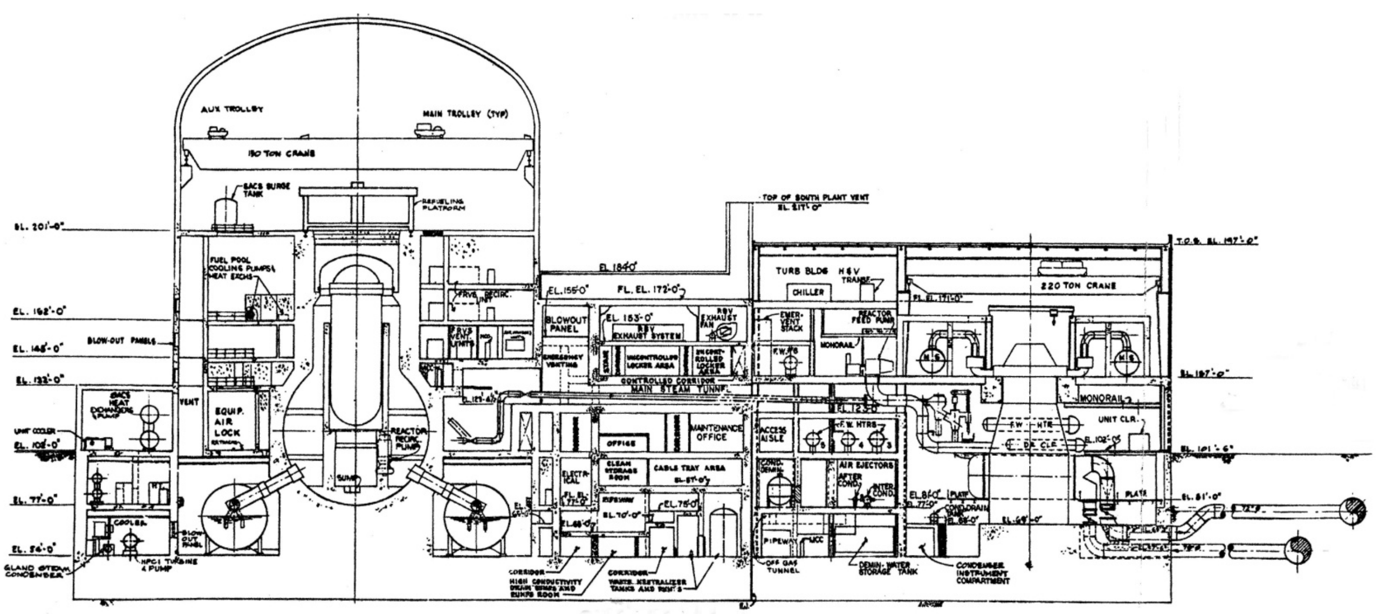


Figure 22. Cutout through containment and turbine hall showing the location of the fuel storage pool in a typical BWR. Plant systems below grade level and hence affected by flooding from the tsunami event include pumps and electrical components. The dry well includes a sump. Any leaking corium material through the control rod seals could interact with the sump water as well as the concrete mat causing a steam explosion, then becoming embedded in the concrete. Source: GE.

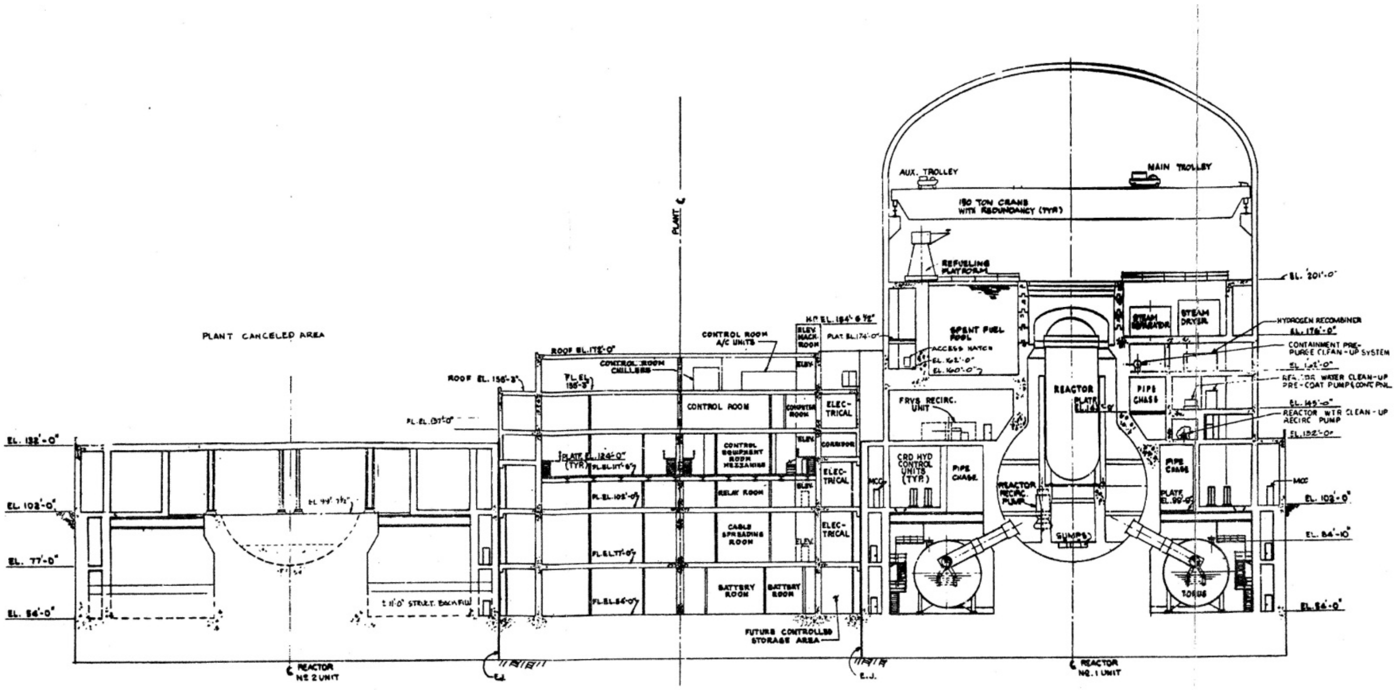


Figure 23. Perpendicular cutout through the containment structure showing the location of the storage batteries. The gate and other connections between the fuel storage pool and the top of the core may have sustained damage as a result of the earthquake and caused leakage of the pools' cooling water. Source: GE.

Figure 24. Tsunami water flooding of electrical switching components in basement of unit 1, May 6, 2011. Source: Tepco.

After depressurization, using the condensate storage tank is an extra available source of cooling water. As an emergency action, sea water was pumped mixed with boric acid or sodium polyborate with boron as a neutron absorber to refill the spent fuel storage pool and to refill the pressure suppression pool. The operators may have to eventually pump sand and gravel into the reactor vessel and entomb it, if significant damage would have occurred.

FISSION PRODUCTS RELEASE

The decay heat cooling needs to be actively continued for at least 24-48 hours. If no cooling is provided the cladding is oxidized forming hydrogen, fuel damage results and a release of fission products into the containment structure ensues. If the pressure suppression system is not able to quench the steam and reduce the pressure in the containment shell, the buildup of pressure in the containment, unless controllably released, would cause it to fail at its weakest links which are the piping and instrumentation penetrations. The earthquake event could have also affected the integrity of these penetrations. In this case the release of the volatile radioactive gaseous species such as I^{131} with a short half-life of 8.04 days, Te^{132} producing I^{132}, and the noble gases $Kr^{87}$and Xe^{131} as a result of fuel damage to the environment takes about 24-48 hours to occur.

The I^{131} isotope is used in Nuclear Medicine applications for the treatment of thyroid nodules and Grave’s syndrome, since iodine tends to accumulate in the thyroid gland. This also makes it a health hazard in the short term in reactor accidents.

The main hazard from the short lived isotopes results from I^{132} which is produced from the fission product Te^{132}: The decay of Te^{132} produces I^{132}. An amount of 38 kilocuries of I^{132} is produced per MWth of reactor power. The Te^{132} released from a reactor accident will also produce I^{132} outside the reactor according to the reaction:

$$_{52}Te^{132} \rightarrow {}_{53}I^{132} + {}_{-1}e^{0} + \nu^{*} + \gamma \quad (7)$$

with a half life of 2.3 hours, which seeks the thyroid gland, and can cause the occurrence of thyroid nodules.

Table 3. Short half life fission products isotopes.

Isotope	Half life	Activity [kCi/MWth]		Boiling point [^oC]	Volatility	Health Physics
		Shutdown	1 day after shutdown			
Br^{83} Br^{84} Br^{85} Br^{87}	2.3 h 32 m 3 m 56 s	3 6 8 15	0 0 0 0	59	Highly volatile	External whole body radiation, moderate health hazard
Kr^{83m} Kr^{85m} Kr^{87} Kr^{88} Kr^{89}	114 m 4.4 h 78 m 2.8 h 3 m	3 8 15 23 31	0 0.2 0 0.1 0	-153	Gaseous	External radiation, slight health hazard

Kr^{90}	33 s	38	0			
I^{131} I^{132} I^{133} I^{134} I^{135} I^{136}	8 d 2.3 h 21 h 52 m 6.7 h 86 s	25 38 54 63 55 53	23 0 25 0 4.4 0	185	Highly volatile	External radiation, internal radiation of thyroid gland, high radio toxicity
Xe^{131m} Xe^{1331m} Xe^{133} Xe^{135m} Xe^{135} Xe^{137} Xe^{138} Xe^{139}	12 d 2.3 d 5.3 d 15.6 m 9.2 h 3.9 m 17 m 41 s	0.3 1 54 16 25 48 53 61	0.3 0.7 47 0 4 0 0 0	-108	Gaseous	External radiation, slight health hazard
Te^{127m} Te^{127} Te^{129m} Te^{129} Te^{131m} Te^{131} Te^{132} Te^{133m} Te^{133} Te^{134} Te^{135}	105 d 9.4 h 34 d 72 m 30 h 25 m 77 h 63 m 2 m 44 m 2 m	0.5 2.9 2.3 9.5 3.9 26 38 54 54 63 55	0.5 0.5 2.3 0 2.2 0 31 0 0 0 0	-	Product of uranium oxidation	External Radiation, moderate health hazard. Health hazard from I^{132} daughter.

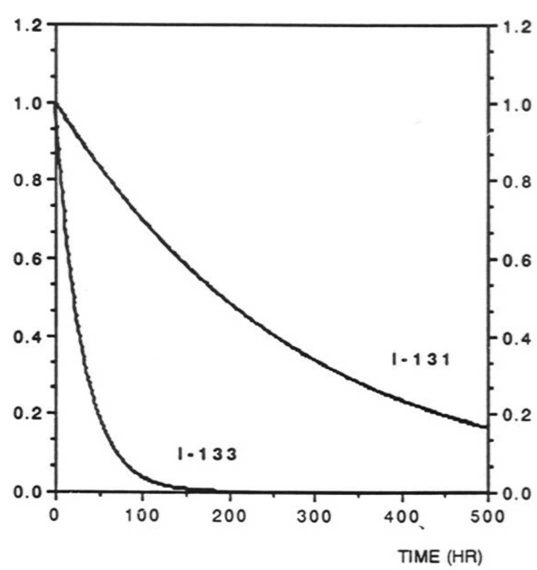


Figure 25. Decay curves of two short lived fission product isotopes, I^{131} and I^{133}.

Table 4. Long half life fission products isotopes.

Isotope	Half life	Activity [kCi/MWth]		Boiling	Volatility	Health

		After 1 year irradiation	After 5 years irradiation	point [^{0}C]		Physics
Kr^{85}	10.4 a	0.12	0.62	-153	gaseous	Slight health hazard
Sr^{89}	54 d	39	39	1366	moderately volatile	Internal hazard to bone and lung
Sr^{90}	28.74 a	1.2	6.0			
Ru^{106}	1.0 a	5	10	4080	Highly volatile oxides (RuO_3, RuO_4)	Internal hazard to kidney and gastro intestinal (GI) tract
Cs^{137}	30.04 a	1.1	5.3	670	Highly volatile	Internal hazard to whole body
Ce^{144}	282 d	30	50	3470	Highly volatile	Internal hazard to bone, liver and lung
Ba^{140}	12.6 d	53	53	1640	Highly volatile	Internal hazard to bone and lung

In the more severe case of a core damage associated with high temperatures, the release of the less volatile fission products such as Cs^{137} and Sr^{90} would occur.

It must be noted that regarding human exposure, the biological half life of Cs^{137} is a short 110 days, whereas the biological half-life of the bone-seeker Sr^{90} is a long 18 years, making it the more serious consideration. On the other hand, Sr^{90} (boiling point = 1,336 ^{o}C) is considered as moderately volatile and is released if higher temperatures are attained in a postulated accident, so that a smaller amount than the highly volatile Cs^{137} (boiling point = 670 ^{o}C) is released. In atmospheric nuclear testing both isotopes are fully released.

The release of Cs^{137} over an ocean area would lead to the formation of cesium hydroxide (CsOH) and its dilution in the vast volume of ocean water.

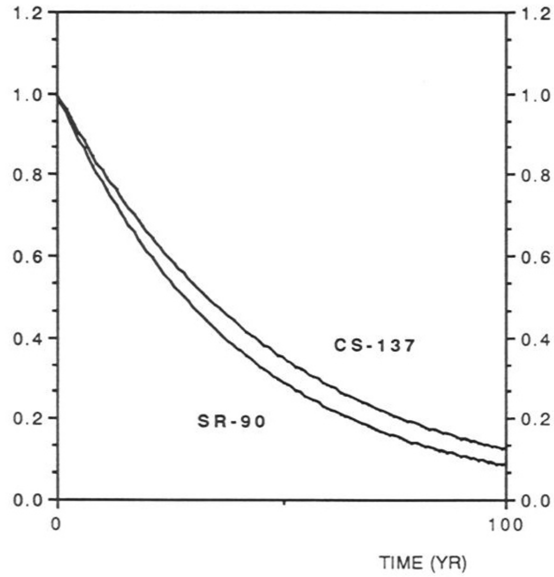


Figure 26. Decay curves of the two long lived fission product isotopes, Cs^{137} and Sr^{90}.

SPENT FUEL STORAGE POOL

Spent fuel is temporarily stored in water to allow for a decrease in the activity of their fission products content. Water also acts as a radiation shield. A typical pool is constructed out of reinforced concrete with an inner steel lining with a 40 x 35 ft base and 39 ft depth comprising the fuel assemblies of 13 ft of length and an ideal water depth of 26 feet above the fuel assemblies.

The fuel assemblies are stored in steel racks with boron added as a neutron absorber to prevent criticality. If the water leaks as a result of earthquake damage or cooling is discontinued, the water level would decrease through evaporation at a rate of 2 ft / day, eventually uncovering the fuel. The heat generation can cause the Zircaloy cladding to oxidize causing the volatile fission products to be released and even the zirconium to catch fire. The pouring of cold water on the hot cladding would generate thermal stresses in the cladding causing it to fail. To avoid causing a partially-drained or dried-out pool, cooling must be maintained.

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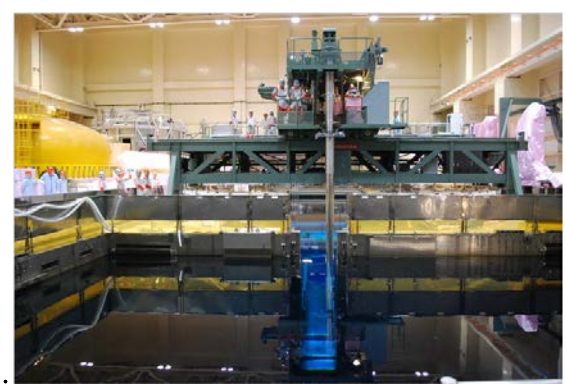

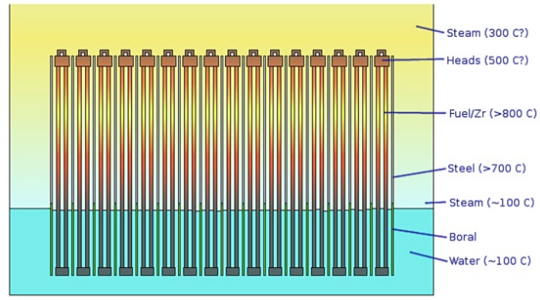

Figure 27. Spent fuel storage pools (top) showing fuel assembly being moved through gate between pool and reactor top. Yellow object is the removed core dome. Steam emanating from fuel storage pool in unit 4 on March 15, 2011, under the loading crane showing at the center of the picture (bottom).

FUKUSHIMA DAIICHI SITE REACTORS

All the 6 units at Fukushima Daiichi Nuclear Power Station were shut down. Radioactivity level was higher than the ordinary level. The level at a monitoring post in the vicinity of the site was higher than the normal level.

Evacuation of local residents within a 20 km radius around the plant was undertaken. Units 1-4 were involved in the accident.

Authorities have raised the maximum allowable radiation dose allowed for the workers in an effort to avoid having to abruptly order them to abandon their posts. About 180 workers were on duty.

Helicopters were used to drop water on the reactors. Water pumped from fire trucks was used to cool a spent-fuel pool that is responsible for significant radioactive releases.

Unit 1

Reactor has been shut down.

About 55 percent of fuel damaged in partial core meltdown. Reactor vessel may have been breached by molten fuel. Water injection to core is 1,600 gallons /hr by April 29, 2011.

Reactor achieved cold shut down condition and reactor coolant water level is stable.

Offsite power is available.

An explosive sound and white smoke, thought to have resulted from a hydrogen explosion, occurred at 3:36 pm, March 12, 2011.

Sea water mixed with boric acid or sodium polyborate was injected into the reactor pressure vessel.

A naval vessel was used to bring-in fresh water for cooling.

On March 25, 2011, fresh water was used and replaced sea water.

On March 25, 2011, The fission products Cs^{136}($T_{1/2}$ = 13.1 d) and Y^{91}($T_{1/2}$= 58.6 d) were found in the water at the turbine hall of unit 1.

Lights were switched on in the control room in the week of March 25, 2011.

Pumps were used to drain the water from the turbine building basement and was stored in tanks to allow the radioactivity to decay.

Figure 28. Damage to the upper structure of the Fukushima Daiichi unit 1, and undamaged structure of unit 2. Source: Tepco.

Unit 2

Reactor has been shut down.
Partial core meltdown with about 35 percent fuel damage. Molten fuel may have breached the pressure vessel. Hydrogen explosion damaged part of primary containment vessel around the core.
Reactor Core Isolation Cooling system, RCIC has been injecting water into the reactor.
Reactor core coolant water level lower than the normal level, but the level is steady.
Lowering of pressure of reactor containment vessel is achieved through steam release.
At 1:25 pm, March 14, water injection into Unit 2's reactor was being carried out by the Reactor Core Isolation Cooling System, RCICS.
A hydrogen explosion may have damaged the pressure suppression pool.
Effective dose rates of 20-30 cSv/hr or rem/hr were found in the water in Unit 2.
Light switched on in the control room on March 26, 2011.

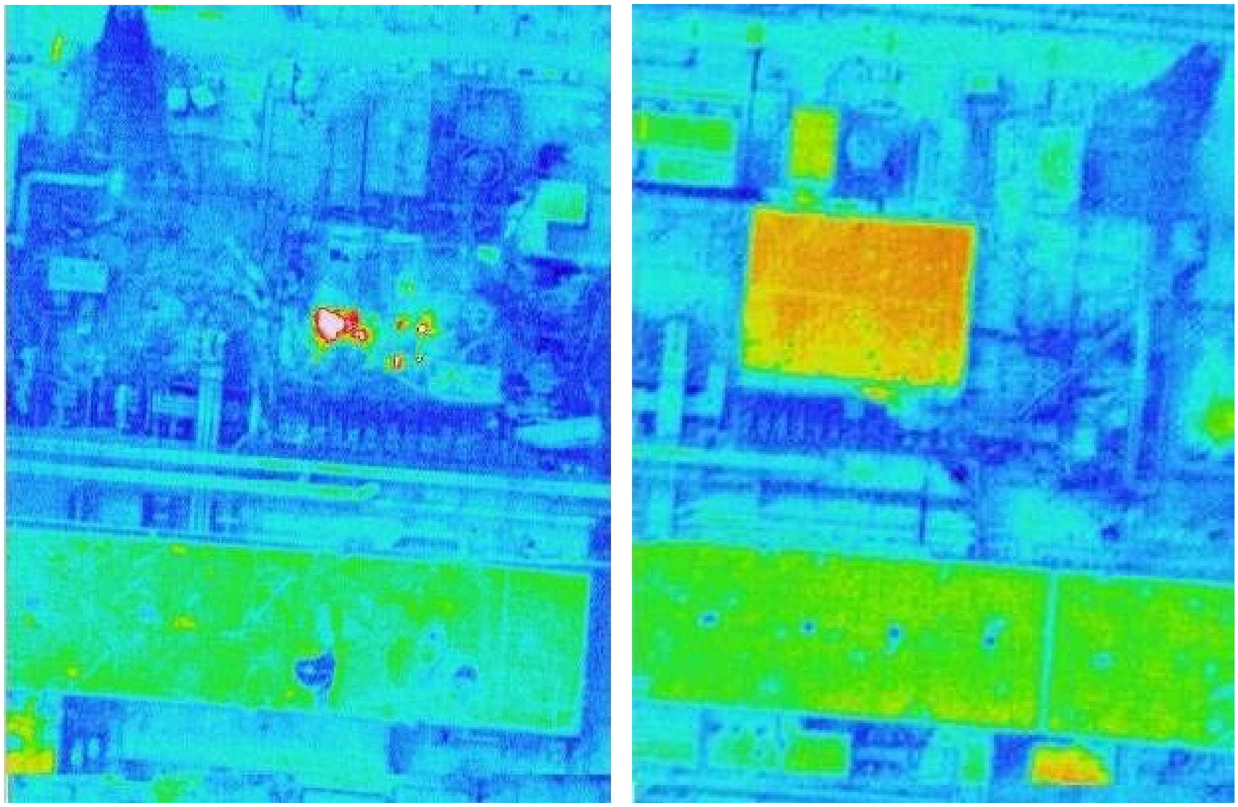

Figure 29. Infrared signatures of Fukushima units 1 and 2 (right) suggesting a temperature of 262 ^{o}F in unit 2 and of units 3 and 4 (left) suggesting a lower temperature of 144 ^{o}F on March 21, 2011 in reactor building and turbine hall caused by accumulated unvented steam. A heat plume at the bottom of the reactor building of unit 2 suggests steam leakage from the undamaged building structure. A heat signature exists in unit 1 to the far right. Unit 4 does not exhibit a heat signature. Highly localized heat signature in unit 3 may suggest a possible ejection of the concrete shield plug by the observed hydrogen or possibly steam explosion. Atmospheric pressure measurements at units 2 and 3, but not unit 1, suggest containment breach by April 10, 2011. Source: Tepco.

Unit 3

Reactor has been shut down.
Partial core meltdown with about 30 percent fuel damage. Containment vessel may have been damaged. Spent fuel pool may have been uncovered.
The High Pressure Core Injection System, HPIS has been automatically shut down and water injection to the reactor was interrupted.
It is likely that a coolant pipe was affected by the earthquake. An unsuccessful attempt was made to start the Emergency Core Cooling System, ECCS within two hours of the earthquake.
Steam release to lower the pressure of the reactor containment vessel was undertaken.
Spraying to lower the pressure level within the reactor containment vessel was cancelled.
Safety relief valve has been manually opened, lowering the pressure level of the reactor.
This was followed by injection of water with boric acid or sodium polyborate into the reactor pressure vessel.

The seawater injection halted for about 2 1/2 hours because the tanks being used went dry, and that stoppage triggered rising pressure in the reactor vessel.
At 11:01 am, March 14, 2011 an explosive sound followed by white smoke occurred at the reactor building. It is believed to be a hydrogen explosion with a reported containment vessel damage.
Lights switched in the control room in the week of March 24, 2011.
As of 11:44 am, March 14, the measured value of the radiation effective dose rate was 20 μSv/hr and the radiation level remains stable. A hydrogen or steam explosion may have occurred with ensuing pressure vessel damage.
An indication that a breach may have occurred in the reactor pressure vessel came up on March 24, 2011 when three workers who were trying to connect an electrical cable to a pump in the basement of a turbine building next to the reactor were injured when they stepped into water that was found to be significantly more radioactive than normal in a reactor. Water samples revealed the existence of Co^{60} ($T_{1/2}$= 5.27 y) and Mo^{99} ($T_{1/2}$= 66.02 h) which are activation products that could have leaked from a condensate polisher in the basement of the turbine building or its piping.
Unit 3 was the only unit of the six reactors at the site that uses the Mixed Oxide, UO_2-PuO_2 MOX fuel, was damaged by a hydrogen explosion on March 14, 2011.
A reported long vertical crack running down the side of the containment vessel implies the possible occurrence of a steam explosion.
A broken pressure vessel is not the only possible explanation: the water might have leaked from another part of the facility.

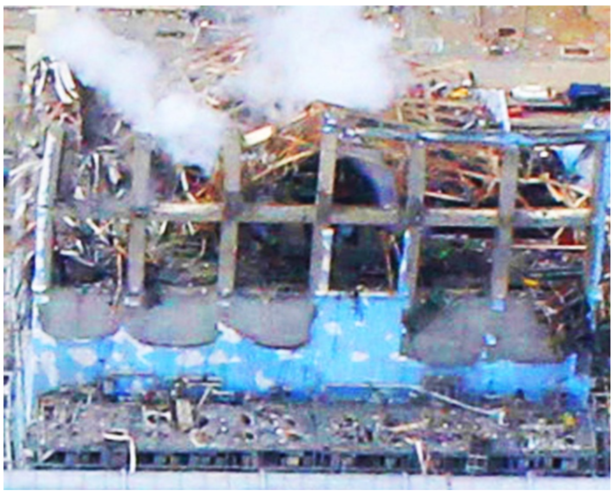

Figure 30. Fukushima Daiichi Unit 3. Steam emission on March 21, 2011 evolved into black smoke. A possible hydrogen or steam explosion tore out the upper part of the containment building structure. The blow-out-panels are missing, with remaining steel and concrete beams. The reactor containment vessel is reported to remain intact, even though the nuclear fuel storage pool and the reactor refueling deck would be exposed to the elements. Steam and dark smoke emanating from possible burning of the UO_2 fuel, concrete rubble, or boron carbide B_4C embedded in the Al of the Boral shielding material if it is used in the fuel storage pool as spacer between the fuel assemblies. Source: Tokyo Electric Power Company.

Unit 4

Reactor was shut down for a routine planned maintenance on November 30, 2010.
All active fuel from the reactor core was earlier transferred to its spent fuel storage pool.
Estimated 125 tons of fuel was stored in the spent fuel storage pool.
Fuel stored in spent fuel pool may have been uncovered. An explosion and fire damaged the building. Water intermittently sprayed in spent fuel pool.
Sufficient level of reactor coolant was initially maintained in the shutdown reactor.
No reactor coolant leakage inside the reactor containment vessel was initially observed.
At 6:00 pm March 15, 2011 an explosion occurred within the previously shut-down unit 4, possibly from steam and hydrogen originating from unit 3.
Fuel storage pool lost its coolant and is thought to have partially gone dry.
The formation of hydrogen implies cladding oxidation of the fuel stored in the spent fuel storage pool.
A fire that lasted 2 hours has been extinguished on March 15. It reignited on March 16 and was re-extinguished.

Figure 31. Fukushima Daiichi unit 4 on March 16, 17, 2011 showing steam emanating from fuel storage pool. Source: Japan Self Defense Force.

Units 5

Reactor was shut down for regular inspection on January 3, 2011.
The building is not damaged.
To prevent radioactivity from becoming airborne, a dust inhibitor was sprayed over 49,000 ft^2 around reactors.
Core is loaded with fuel.
Sufficient level of reactor coolant is maintained.
No reactor coolant leakage inside the reactor containment vessel.
Operators considered removal of panels on reactor building to prevent the buildup of hydrogen.
Temperatures rising on March 16.

Units 6

Reactor was shut down for regular inspection on August 14, 2011.
The building is not damaged.
Temperature in fuel storage pool is 78 ^oF, with the normal temperature being 77 ^oF.
Power from an emergency diesel generator replaced from external source.
Core loaded with fuel.
Sufficient level of reactor coolant is maintained.
No reactor coolant leakage inside the reactor containment vessel.
Operators considered removal of panels on reactor building to prevent buildup of hydrogen.
Temperature rising on March 16.

FUKUSHIMA DAIINI SITE REACTORS

All four units as of March 29, 2011 were in cold shutdown status with stable water coolant level and offsite power available to the units.

No leakage of reactor primary coolant to the containment vessel. A range of water temperature below 100 ^oC is maintained in the Pressure Suppression Pool.

Radioactivity monitoring stations at the site boundary did not show any difference from the background level.

No radioactive material was discharged from exhaust stack or discharge canal.

Unit 1

Shut down at 2:48 pm on March 11th, 2011.
Average coolant water temperature maintained at 100 ^oC.
At 8:19 am, March 12th, an alarm indicating that one of the control rods was not properly inserted
At 10:43 am, March 12th the alarm was spontaneously called off.
Other control rods are fully inserted.
Main steam isolation valves are closed.
Injection of water into the reactor is achieved using the Make-up Water Condensate System.
No observed leakage of reactor coolant in the containment vessel.
At 5:22 am, March 12th, the temperature of the pressure suppression pool exceeded 100 ^oC.
As the reactor pressure suppression function was lost, at 5:22 am, March 12th, it was decided to prepare implementing measures to reduce the pressure of the reactor containment vessel by partial discharge of steam.
The preparation work started at around 9:43 am, March 12th and was finished at 6:30 pm, March 12th.
Restoration of cooling function achieved reactor cold shutdown.
Injection of nitrogen into the containment was carried out to force a purging of any accumulated hydrogen.

Unit 2

Shut down at 2:48 pm on March 11th, 2011.
Reactor achieved cold shut down condition and reactor water level is stable.
Offsite power is available.
Average coolant water temperature maintained at 100 ^oC.
Control rods are fully inserted and reactor is in subcritical condition.
Main steam isolation valves are closed.
Injection of water into the reactor is done using the Make-up Water Condensate System.
No observable leakage of reactor coolant in the containment vessel.
At 5:32 am, March 12th, the temperature of the suppression chamber exceeded 100 degrees C.
As the reactor pressure suppression function was lost, at 5:32 am, March 12th, it was decided to prepare implementing measures to reduce the pressure of the reactor containment vessel by partial discharge of steam.
The preparation work started at around 10:33 am, March 12th and finished at 10:58 pm, March 12th.
Restoration of cooling function achieved reactor cold shutdown.

Unit 3

Shut down at 2:48 pm on March 11th, 2011.
Reactor achieved cold shut down condition and reactor coolant water level is stable.
Offsite power is available.
Average coolant water temperature maintained at 100 ^oC.

Control rods are fully inserted and reactor is in subcritical condition.
Main steam isolation valves are closed.
No observable leakage of reactor coolant in the containment vessel.
Preparation for implementing measures to reduce the pressure of the reactor containment vessel by partial discharge of steam.
Preparation work started at around 12:08 pm, March 12th and finished at 12:13 pm, March 12th.
Reactor cold shutdown at 12:15 pm, Mar 12th 2011.

Unit 4

Reactor is shut down and reactor water level is stable.
Offsite power is available.
At 0:43 pm, there was a false positive signal indicating that one of the control rods may have not been properly inserted.
It was confirmed that it was inserted completely by another signal.
Main steam isolation valve is closed
Injection of water into the reactor is by means of the Make-up Water Condensate System.
No observable leakage of reactor coolant in the containment vessel.
To cool down the reactor, injection of water into the reactor is undertaken by the Reactor Core Isolation Cooling RCIC system.
At 6:07 am, March 12th, the temperature of the pressure suppression pool exceeded 100 degrees C. As the reactor pressure suppression function was lost, at 6:07 am, March 12th, it was decided to prepare for implementing measures to reduce the pressure of the reactor containment vessel by partial discharge of steam.
Preparatory work was started at around 11:44 am, March 12th and was finished at around 11:52 am, March 12th.
Restoration work in reactor cooling function achieved reactor cold shutdown.

HYDROGEN AND STEAM EXPLOSIONS

Figure 32. Steam appears to be leaking from top of left containment structure prior to hydrogen explosion. Source: Reuters.

Figure 33. Fukushima Daiichi unit 1 Boiling Water Reactor, BWR nuclear power plant horizontally propagating hydrogen explosion, initiated by depressurization and steam venting, sequence of events. March 12, 2011.

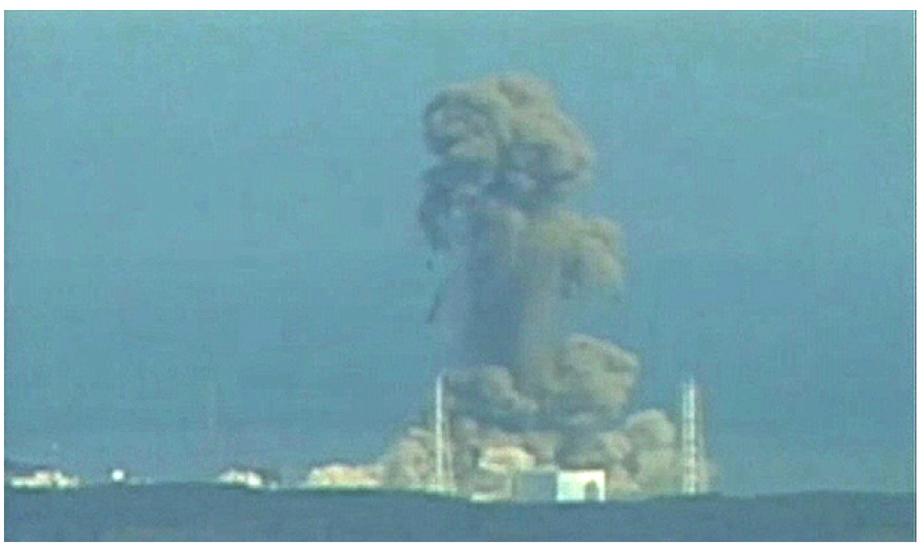

Figure 34. Highly energetic vertically propagating hydrogen or possibly steam explosion (left) at the Fukushima Daichi unit 3 BWR on March 14, 2011 was followed by a fire and reactor fuel damage. Heavy debris possibly composed of the concrete shield plug or crane components was vertically ejected and is seen falling back down in the photograph. No damage to the reactor vessel can be inferred from the absence of the reactor's top plug in the ejecta. It bears some analogy to the complex aerodynamics of an "exploding vortex ring." Sources: NTV / NNN, Japan.

If the cooling system remains inoperative for many hours, the water would eventually boil away, the cladding would oxidize, and the fuel would begin to melt. Hydrogen can be formed from the steam and the metallic Zircaloy cladding interaction:

$$H_2O + Zr \rightarrow ZrO + H_2 \tag{8}$$

without a venting or a controlled burn of the generated hydrogen in plants equipped with hydrogen recombiners, a pressure pulse can be generated from the hydrogen interaction with the oxygen in the containment atmosphere:

$$2H_2 + O_2 \rightarrow 2H_2O \tag{9}$$

A suspected hydrogen pressure pulse has been in fact reported in the Three-Mile Island accident but it did not cause any significant damage to the containment system to the degree observed at the Fukushima event.

One ton of Zr can interact with 792 lbs of water to generate 88 lbs of H_2 gas. Each meter length of fuel rods cladding contain about 15.4 tons of Zr.

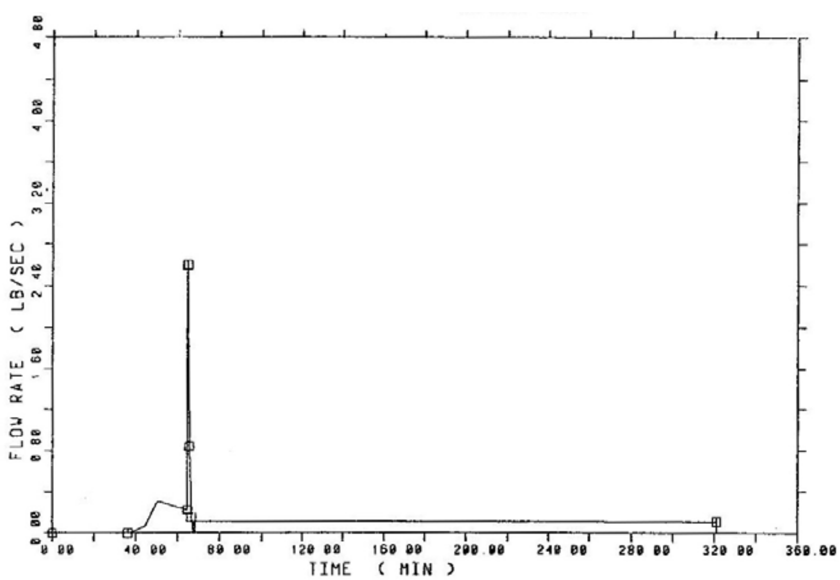

Figure 35. Hydrogen release rate was correlated with a pressure pulse inside the containment structure in the Three-Mile Island Accident. The hydrogen pulse did no discernible damage to the containment structure.

Water suddenly evaporating into steam expands to a large volume. A familiar event is the sudden flashing into steam when the cap of an automobile radiator is inadvertently opened with the water under pressure. When the pressurized water senses the lower atmospheric pressure than in the pressurized radiator and reaches its saturation pressure, it flashes into steam, and the coolant in the radiator is lost. Another familiar event is the explosive expansion of the water inside the popcorn kernel leading to its popping.

Steam explosions were observed in the steel industry when ingots of cast steel were suddenly quenched in water. The sudden quenching leads to the disintegration of the molten steel with a large heat transfer area leading to evaporation of the water into steam and its explosive expansion.

Yet other similar occurrences are dust explosions during delivery at the grain elevators in the American Midwest. As grain is dumped into the storage pits, dust is released in substantial quantities. With its large surface area, the dust can be ignited by a triggering event such as a spark from a starting motor or a lighted cigarette, causing a deflagration and significant damage.

Another situation is one where the core melts down with the molten corium material melting through the steel reactor vessel and embedding itself into the reactor concrete base mat. In the case of a faulty design such as the RBMK-1000 with the water in the pressure suppression pool directly placed underneath the reactor core, a steam explosion can occur like in the Chernobyl accident. It is worth noting that in the GE BWR designs Mark I design, the pressure suppression pool is located at a lower level below the core, but not directly under it precluding a serious form of steam explosion. However, a sudden depressurization can still lead to sudden flashing of the pressurized water into steam and an explosive expansion with an associated loss of coolant available to cool the core.

Fragments or particles of nuclear fuel from the spent fuel pools above the reactors were blown “up to one mile from the units” and pieces of highly radioactive material reportedly fell between two units (presumably 3 and 4) and had to be “bulldozed over,” to protect workers at the site. The ejection of fuel parts from unit 3 would imply a more serious event than a hydrogen explosion in the form of a criticality excursion and a steam explosion associated with a core meltdown.

It has been suggested that a more logical location for the pressure suppression pool is above the reactor core, avoiding such an eventuality and offering the benefit of providing passive natural circulation convection cooling of the core, upon equalizing the pressure between the core and the pressure suppression pool, without the need for active pumping requiring power supplies. Equally important would be the elimination of the possibility of molten corium material with water causing a steam explosion.

Figure 36. Damaged core resulting from steam explosion caused by a criticality accident in the military Small Low power reactor experiment SL-1 BWR. A worker inadvertently yanked out a

control rod beyond the set limit during a maintenance procedure. The core became supercritical, boiled off the steam causing a steam explosion. The drying of the moderator stopped the fission reaction, even though the decay heat generation would have persisted for a while.

LEAK BEFORE BREAK, VESSEL LEAKAGE OR MELT-THROUGH

Richard Lahey, head of safety research for boiling-water reactors at the General Electric Company, suggested that at least part of the corium material which includes melted fuel rods and Zircaloy cladding, may have sunk through the steel lower head of the pressure vessel in unit 2 and that at least some of it is down on the floor of the drywell.

The major concern when molten fuel breaches a containment vessel is that it reacts with the concrete floor of the drywell underneath it, releasing gases such as CO, CO_2, H_2 and steam into the surrounding area. At the Fukushima unit 2, the drywell has been flooded with seawater, which will cool any molten fuel that would escape from the reactor, but could also cause a steam explosion.

The corium material would not come out as a big glob, but rather it would leak out like lava. This is desirable since it is easier to cool.

The drywell is surrounded by a secondary steel-and-concrete structure designed to keep radioactive material from escaping into the environment. However an earlier hydrogen explosion may have damaged it.

The reason for the suggestion is the detection of water outside the containment area that is highly radioactive and it can only have come from the reactor core. The effective dose rate at a pool of water in the turbine hall of unit 3 was reported on March 25, 2011 as 20 cSv/hour or 20 rem/hr of gamma radiation. For a USA maximum occupational yearly effective dose of 5 rems, emergency workers would be allowed to remain in the area for (5 x 60) / 20 = 15 minutes.

The ground effective radiation dose outside the reactor structures is significantly lower, reported at 0.2 cSv/hr or 0.2 rem/hr. It is even lower at nearby communities such as the Iitate village at 40 km northwest of the site at 0.0013 cSv/hr or rem/hr, and at Fukushima City at 61 km northwest of the site at 0.0008 cSv/hr or rem/hr.

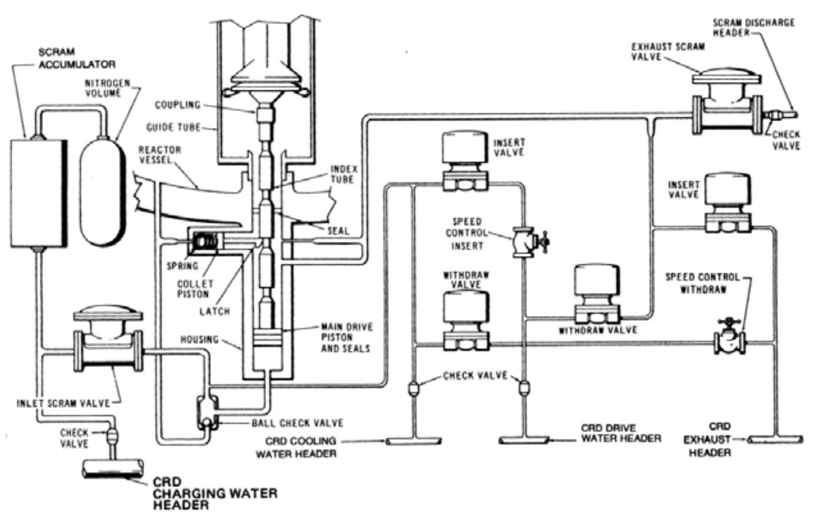

Figure 37. BWR control rod drive mechanism at the bottom of a BWR reactor vessel showing the control rod graphite seals location [2].

Based on the principle of “leak before break” in accident analysis, another explanation has been advanced for the occurrence as being possibly related to leakage through the control rod seals at the bottom of the reactor vessel. Boiling water reactors have their control rods inserted from the bottom of the cores. They are equipped with a graphite stopper covering each control rod penetration that seals the primary cooling water. At temperatures above 350 ^{o}F, the graphite stoppers mechanical properties would begin to deteriorate.

It was suggested that as the debris from the damaged fuel rods collected at the bottom of the reactor vessel, the seals may have been damaged by high temperature. If the graphite seals fail, water in the reactor would leak into a network of pipes in the containment structures and auxiliary buildings associated with the reactor.

ACCIDENT RESPONSE AND MITIGATION EFFORTS

Initially, about 3,000 residents within a 1.8 mile or 3 km radius of Tokyo Electric Power's, Tepco Fukushima Daiichi nuclear plant were evacuated. The larger number of residents within a radius of 6.2 miles or 10 km, were initially advised to stay inside their residences. The risk from accidents resulting from panicky evacuation driving on the road system would exceed the risk of whole body irradiation from the released gaseous fission products indoors.

Later on, 45,000-51,000 residents within the 10 km radius were advised to evacuate. The evacuation radius was extended to 12 miles or 20 km with 77,000 residents. Eventually residents within a 12-19 miles radius with another 62,000 residents for a total of 132,000 residents were advised to evacuate. Some communities with high radiation levels beyond the designated evacuation zones were advised to evacuate. The USA embassy in Tokyo advised USA citizens to evacuate within a 50 miles radius based on intelligence obtained from satellite and airplane sampling meant for clandestine nuclear activities and testing monitoring.

The recommendation is based on an evacuation model prediction of possible radiation levels assuming a degradation of plant conditions including possible containment system failure and weather patterns. It is not based on actual radiological conditions.

Table 5. Evacuation zones around the Fukushima plant site based on worst-case evacuation model. March 16, 2011.

Radius [miles]	Possible effective dose [cSv, rem]	Population
0.5	5,400	29,000
1.0	1,500	
1.5	670	
2	390	
3	180	
5	75	
7	40	33,000
10	14	

15	15	37,000
20	13	50,000
30	11	345,000
40	10	979,000
50	10	571,000

Tokyo Electric Power released steam at the plants to relieve the reactor containment structure pressure and to exhaust the accumulated potentially reactive hydrogen gas that resulted from the oxidation of the fuel cladding and its damage.

With an ocean-bound wind direction the released gaseous fission products would harmlessly decay, dilute and dissipate over the Pacific Ocean. The composition of the released fission products depends on the temperature reached by the damaged fuel. Cs^{137} appears to have been released, but no measurements about the release of the less volatile Sr^{90} were reported.

Water levels inside the reactor core fell as a result of a power loss to its Emergency Core Cooling System, ECCS. Emergency diesel generators assure the ability to continue cooling even during a station blackout. Many reactors have two or three diesel generators for redundancy.

The Tepco utility had been operating three out of six reactors at the Fukushima Daiichi nuclear plant at the time of the earthquake. Three out of six units were affected by the loss of cooling. The other three reactors at the plant were in a shut-down state for a planned maintenance.

Eleven nuclear reactors were automatically shut down in the wider quake-affected areas of Japan. A fifth of the country's total nuclear generating capacity was temporarily taken offline because of the earthquake and restored within 50 minutes.

With the inability to start the decay heat removal system and the Emergency Core Cooling System, ECCS, fresh cooling water was pumped into the cooling system.

A back-up battery power system with about 8-12 hours of operational storage capacity had been brought online after about an hour and helped initiate the process of pumping water back into the cooling system, where the water level had been falling.

At the onset of the earthquake the water level was 3.4 meters or about 10 feet above the fuel rods at the unit 2 reactor at the plant.

Fukushima 1, which was designed by General Electric and entered commercial service in 1971, was designed to function for 4-8 hours under natural circulation cooling without emergency diesel generators.

Such reactors had pumps that could be powered by steam, which would still be available in case of electric power failure. Valves can be opened by motors that run off batteries. Older plant designs, of the era of Fukushima, generally have batteries sized to operate for four hours. After four hours, the decay heat production in the core is still substantial and must be removed for at least 24-48 hours as it decays exponentially. The heat, if not rejected, would boil away the cooling water, raising pressure in the reactor vessel, until automatic relief valves opened to let some of the steam out. Then the valves would close and the pressure would start building again.

If the containment ventilation system is operable, the vented air is routed through High Efficiency Particulate Air, HEPA filters, gas adsorption activated charcoal beds, lowering any fission product releases by a factor of 100-1,000.

RADIONUCLIDES RELEASE

A crisis management system that existed since 1986 was managed by a group of advisers that did not know about the resources available to them until March 16, 2011, such as the System for Prediction of Environmental Emergency Dose Information, Speedi. The Speedi system predicted that the radiation plume from the accident would diffuse to the northwest, but that information was not used. People evacuated north based on the reasoning that winds usually blew south during the winter in that area, and were unnecessarily exposed to the plume.

Monitoring vehicles collected air samples and measured the activity density of the radionuclides of concern at the western gate of the Fukushima Daiichi site. The samples were analyzed at the Fukushima Daiini plant site using a Germanium solid-state counter for a measuring time of 500 s. $Iodine^{131}$ reached just 45 percent of the statutory activity density level for workers engaged in tasks associated with radiation.

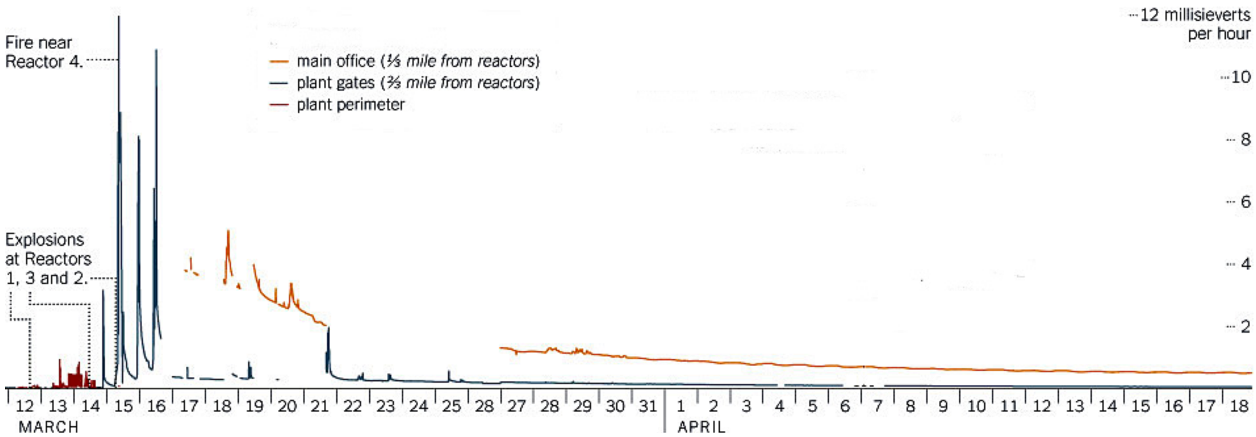

Figure 38. Effective dose rate measurements at main office, plant gates and plant perimeter. Source: Tepco, NY Times.

Table 6. Nuclides Analysis in the air at the Fukushima Daiichi Western Gate, March 27, 2011. Data: Tepco.

	Nuclide	Activity density [Bq/cm^3]	Detection limit [Bq/cm^3]	Statutory activity density limit to the 3-month average in the air to workers engaged in tasks associated with radiation [Bq/cm^3]	Activity density ratio
Volatiles	Co^{58}	-	-	1.0×10^{-2}	-
	I^{131}	4.5×10^{-4}	8.2×10^{-6}	1.0×10^{-3}	0.4500
	I^{132}	1.8×10^{-4}	1.3×10^{-4}	7.0×10^{-2}	0.0026
	I^{133}	-	-	5.0×10^{-3}	-
	Cs^{134}	1.2×10^{-5}	6.4×10^{-6}	2.0×10^{-3}	0.0060
	Cs^{136}	-	-	1.0×10^{-2}	-
	Cs^{137}	1.4×10^{-5}	6.2×10^{-6}	3.0×10^{-3}	0.0047
Particulates	Co^{58}	-	-	1.0×10^{-2}	-

	I^{131}	2.1×10^{-4}	9.5×10^{-6}	1.0×10^{-3}	0.2100
	I^{132}	-	-	7.0×10^{-2}	-
	Cs^{134}	1.6×10^{-5}	8.8×10^{-6}	2.0×10^{-3}	0.0080
	Cs^{136}	-	-	1.0×10^{-2}	-
	Cs^{136}	1.4×10^{-5}-	9.5×10^{-6}	3.0×10^{-3}	0.0047
Other detected nuclides	Te^{129}	2.6×10^{-2}	2.2×10^{-2}	4.0×10^{-1}	0.0650
	Te^{129m}	1.9×10^{-4}	1.5×10^{-4}	4.0×10^{-3}	0.0475
	Te^{132}	1.2×10^{-4}	5.7×10^{-6}	7.0×10^{-3}	0.0171

Larger activity densities were detected in the sampled sea water by measuring 500 ml for 1,000 seconds in a Germanium solid state detector. Most are short lived isotopes except for Cs^{134} with a 2 years half life, and Cs^{137} with a 30.17 years half life.

Table 7. Nuclides Analysis in sea water at the Fukushima Daiichi 30 m north from the discharge canal of units 5 and 6, March 29, 2011. Data: Tepco.

Nuclide	Half Life	Activity density [Bq/cm^3]	Detection limit [Bq/cm^3]	Statutory activity density limit to the 3-month average in the air to workers engaged in tasks associated with radiation [Bq/cm^3]	Activity density ratio
I^{131}	8.041 d	$2.7 \times 10^{+1}$	4.2×10^{-2}	4.0×10^{-2}	665.8
Cs^{134}	2.062 a	$5.6 \times 10^{+0}$	3.2×10^{-2}	6.0×10^{-2}	93.8
Cs^{136}	13.10 d	5.6×10^{-1}	3.2×10^{-2}	3.0×10^{-1}	1.9
Cs^{137}	30.17 a	$5.7 \times 10^{+0}$	2.8×10^{-2}	9.0×10^{-2}	63.5
Ba^{140}	12.79 d	8.8×10^{-1}	1.2×10^{-1}	3.0×10^{-1}	2.9
La^{140}	40.23 h	3.7×10^{-1}	8.5×10^{-3}	4.0×10^{-1}	0.9

Japan’s Food Sanitation Act provides “indices relating to the limits on food and drink ingestion,” indicated by the Nuclear Safety Commission of Japan. Materials exceeding a specific activity of 100 Bq/kg cannot be used in milk provided for use in powdered baby formula or for direct drinking by infants. Contaminated spinach and milk were withdrawn from the market.

Table 8. Ingestion limits of nuclides specific activity in food and drink in Japan.

Nuclide	Source	Specific activity [Bq/kg]
I^{131}	Drinking water Milk, dairy products	300
	Vegetables (Except roots and tubers)	2,000
Cs^{137}	Drinking water Milk, dairy products	200
	Vegetables	500

	Grains Meat, eggs, fish, etc.	
U	Infant foods Drinking water Milk, dairy products	20
	Vegetables Grains Meat, eggs, etc.	100
Tranuranics Pu^{238}, Pu^{239}, Pu^{240}, Pu^{240}, Am^{241}, Cm^{242}, Cm^{243}, Cm^{244}	Infant foods Drinking water Milk, dairy products	1
	Vegetables Grains Meat, eggs, fish, etc	10

Seawater in the close vicinity the plant was reported to have a level of the fission product Sr^{90} that is 240 times the Maximum Permissible Concentration (MPC).

TRANSFORMER FIRE AT ONAGAWA PLANT

The Onagawa plant site is reportedly situated about 15 meters above sea level which could have better protected it against the flooding damage from the tsunami wave.

Japan's Nuclear and Industrial Safety Agency, NISA reported that a fire broke out at the Onagawa plant’s at the Miyagi Prefecture. An electrical transformer caught fire because of overload as a result of the earthquake.

Figure 39. Burning electrical transformer resulting from the coupled earthquake and tsunami event, March 11, 2011. Source: Japan Coast Guard.

The plant is about 45 miles north of the city of Sendai, which was badly damaged by the earthquake and tsunami. Sendai is the population center nearest the epicenter of the earthquake.

The three reactors at the Onagawa site were safely shutdown. The key buildings in the Onagawa plant are about 15 meters above sea level, according Tohoku Electric Power, owner of the plant.

COOLANT LEAKS

The Fukushima Daini and Fukushima Daiichi power plants are separate facilities located in different towns in northeastern Japan's Fukushima prefecture. Each one has its own set of individual nuclear reactors.

The cooling system had failed at three of the four such units of the Daiini plant. Temperatures of the coolant water in that plant's indicated cooling system failure.

Authorities ordered residents within 3 kms of that facility to evacuate as a precaution. That plant was also added to the Japanese nuclear agency's emergency list, along with the Daiichi plant.

Pressure relief valves were activated in that plant, as well as the other Daiichi plant's unit 1 reactor. This is done to release growing steam pressure inside both plants.

AFTERSHOCKS

An aftershock occurred on April 7, 2011 with 7.1-7.9 Richter scale magnitude. Workers were temporarily evacuated from the Fukushima Daiichi site.

The single unit Higashidori BWR and the Rokkasho fuel reprocessing plant lost off-site power and initiated on-site diesel generators.

Offsite power may have been lost to the three units Onagawa plant, but on-site remained available.

Another 6.3 scale aftershock on April 12, 2011, initiated a fire in a battery bank that was quickly extinguished.

Figure 40. Fire in a battery bank initiated by a 6.3 scale aftershock on April 12, 2011. Source: Reuters.

CONSEQUENCES

About 16,000 people lost their lives and 3,000 are missing in the unprecedented combined earthquake and tsunami event, with destruction or damage to 20,820 structures. Millions of people were left without shelter, water or heat. The authorities distributed 230,000 units of stable iodine to evacuation centers from the area around the Fukushima Daiichi and Fukushima Daiini nuclear power plants. The ingestion of stable iodine can help to prevent the accumulation of radioactive Iodine^{131} in the thyroid gland.

A seriously injured worker was trapped within Fukushima Daiichi unit 1 in the crane operating console of the exhaust stack, and two missing Tepco workers were later reported as drowning casualties in the flooded turbine hall of the plant.

Four workers were injured by the hydrogen explosion, a contractor was found unconscious and taken to hospital, two workers of a cooperative firm were injured, one with a broken bone, have been hospitalized

At Fukushima Daiini unit 3, one worker received an effective dose of 10.6 cSv or rem. Other radiation excessive exposure incidents are likely to be identified.

COMMON MODE FAILURE OCCURENCE

PROBABILISTIC ESTIMATION

The probability of the occurrence of two events according to the AND logical gate is:

$$P(A.AND.B) = P(A).P(A\,|\,B) = P(B).P(B\,|\,A)$$

$$\begin{aligned} where: P(A) &\quad \text{is the probability of occurence of event A} \\ P(A\,|\,B) &\text{ is the conditional probability of occurence of event A, given that B occurs} \\ P(B\,|\,A) &\text{ is the conditional probability of occurence of event B, given that A occurs} \end{aligned} \tag{5}$$

If the events A, B are independent, the conditional probabilities become:

$$\begin{aligned} P(A\,|\,B) &= P(A) \\ P(B\,|\,A) &= P(B) \end{aligned} \tag{11}$$

Thus, when A, B are independent events:

$$P(A.AND.B) = P(A).P(B) \tag{12}$$

If the probabilities of occurrence of an earthquake and a tsunami are taken as:

$$P(Earthquake) = P(Tsunami) = 10^{-4}$$

If they are treated as *dependent* events, then:

$$\begin{aligned} P(Tsunami.AND.Earthquake) &= P(Tsunami)P(Tsunami \mid Earthquake) \\ &= 10^{-4} \times 1 \\ &= 10^{-4} \\ where: P(Tsunami \mid Earthquake) = 1 \end{aligned}$$

If one considers the two events as being *independent* we get from Eqn. 5:

$$\begin{aligned} P(Tsunami.AND.Earthquake) &= P(Tsunami)P(Tsunami) \\ &= 10^{-4} \times 10^{-4} \\ &= 10^{-8} \end{aligned}$$

which would be a large underestimate.

The probability of both an earthquake and a tsunami event as a "common mode failure" event may have been underestimated. The two events may have been considered as independent events. As independent events, their estimated probability of occurrence would be substantially less than a common mode failure event.

POSSIBILISTIC ESTIMATION

From a different perspective, if we attempt a possibilistic rather than a probabilistic estimation, the corresponding possibilities would be:

$$\Pi(Tsumami.OR.Earthquake) = Max[\Pi(Tsunami), \Pi(Earthquake] \tag{13}$$

$$\Pi(Tsunami.AND.Earthquake) = Min[\Pi(Tsunami, \Pi(Earthquake)] \tag{14}$$

If we assume the numerical values for the possibilities:

$$\begin{aligned} \Pi(Earthquake) &= 10^{-4} \\ \Pi(Tsunami) &= 10^{-5} \end{aligned}$$

we get the following events possibilities:

$$\begin{aligned} \Pi(Tsunami.OR.Earthquake) &= Max(10^{-5}, 10^{-4}) = 10^{-4} \\ \Pi(Tsunami.AND.Earthquake) &= Min(10^{-5}, 10^{-4}) = 10^{-5} \end{aligned}$$

which suggests that the possibility of the simultaneous occurrence of the two events is the least of the two possibilities.

HYDRAZINE AS A COOLANT

Hydrazine, N_2H_4 was used in conjunction with fresh water in the unit 3 spent fuel pool cooling and filtering system. Even though toxic, it is used as a jet fuel mixed with methanol and rocket thrusters fuel, and to reduce metal salts to pure metals in Pu extraction from nuclear reactor waste and nickel plating. The practice is not encouraged due to the associated process of Flow Accelerated Corrosion, FAC.

It is a useful reductant with ammonia, N_2 and H_2O as products from the exothermic reactions:

$$
\begin{aligned}
&N_2H_4 \rightarrow N_2 + 2H_2 \\
&3N_2H_4 \rightarrow 4NH_3 + N_2 \\
&4NH_3 + N_2H_4 \rightarrow 8H_2 + 3N_2
\end{aligned}
$$

It is used as an anti-oxidant, as an oxygen scavenger and as a corrosion inhibitor in water boilers and heating systems.

USE OF SEA WATER AS A COOLANT

The manager of the plant ignored orders to stop pumping seawater out of fear of recriticality in the fuel storage pools and damaged cores, to release the decay heat generation. Sea water injection was the only means available to cool the cores. The guidelines from the International Atomic Energy Agency, IAEA, specify that the technical decisions in such a situation should be left to the plant managers since a timely response is crucial.

As an emergency option, sea water was used for the first time for cooling the reactors and was added to the spent fuel storage pools. If no chain reaction is occurring, the only concern would be its corrosion effect. To restart the electrical equipment, it would have to be washed of the salt water.

If neutrons are present from a nuclear chain reaction, activation of the chlorine and sodium in the salt would only cause a personnel access concern.

Sodium activation of its single isotope Na^{23} leads to the radioactive species Na^{24}:

$$
{}_0n^1 + {}_{11}Na^{23} \rightarrow {}_{11}Na^{24}(T_{1/2} = 14.95\,hr) + \gamma \ , \tag{15}
$$

while the chlorine two isotopes activate into:

$$
\begin{aligned}
&{}_0n^1 + {}_{17}Cl^{37} \rightarrow {}_{11}Cl^{38}(T_{1/2} = 37.24\,\mathrm{min}) + \gamma \\
&{}_0n^1 + {}_{17}Cl^{35} \rightarrow {}_{11}Cl^{36}(T_{1/2} = 3.01\times 10^5\,y) + \gamma
\end{aligned} \tag{16}
$$

The Na^{24} would remain localized as a short term source of powerful 2.754 MeV gamma photons.

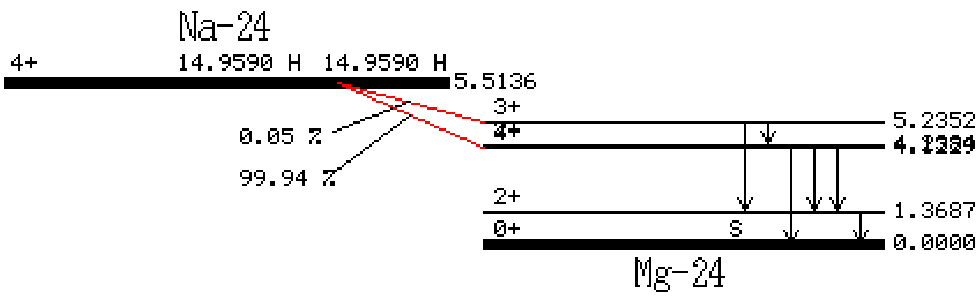

Figure 41. Decay diagram of Na^{24}.

The chlorine isotopes would remain in the NaCl salt. The Cl^{36} has a long half life, hence low activity, and is a pure beta emitter with no gamma radiation. The Cl^{38} isotope would become a short term high activity source of gamma radiation with photon energies of 1.64 and 2.17 MeV.

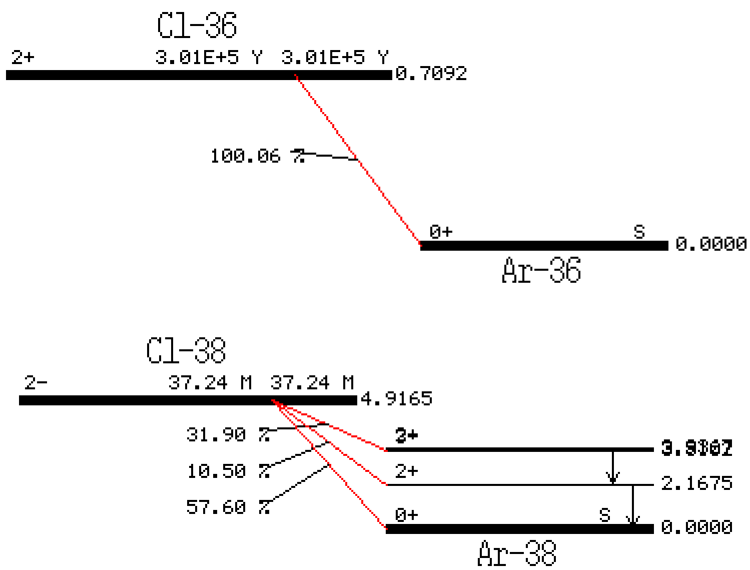

Figure 42. Decay diagrams of the Cl^{36} and Cl^{38} isotopes.

Priyadarshi, Dominguez and Thiemens at the University of California, San Diego, reported the detection of a minute amount above the normal background level of the isotope $Sulfur^{35}$, as part of work on climate research [18]. The incident fascinated scientists because, even though cosmic radiation can produce S^{35} as it interacts with argon nuclei in the atmosphere, nuclear reactors do not produce sulfur as a fission product. The radioactive isotope S^{35} of sulfur was found to have originated from the reactors of the damaged Fukushima Daiichi nuclear plant. There were 1,500 atoms of $Sulfur^{35}$ per square meter in the air in La Jolla, California. The readings were made between March 22 and April 1, 2011. The $Sulfur^{35}$ took about 7 days to cross the Pacific Ocean. It is a short lived isotope with a half life of 87.2 days, is a pure beta emitter without gamma emissions. Its origin can be attributed to the (n, p) hydrogen producing reaction:

$$ {}_0n^1 + {}_{17}Cl^{35} \rightarrow {}_{16}S^{35}(T_{1/2} = 87.2d) + {}_1p^1 \tag{17} $$

It decays back into the original stable isotope Cl^{35} according to the reaction:

$$ {}_{16}S^{35}(T_{1/2} = 87.2\,d) \rightarrow {}_{17}Cl^{35} + {}_{-1}e^0 \tag{18} $$

The vaporized sulfur released with the steam oxidized into sulfur dioxide SO_2 gas then sulfate SO_4^{-2} particles and transported over the Pacific Ocean by westerly winds. The fluence or integrated neutron flux is estimated at 4 x 10^{11} [neutrons / m^2]. The concentration in the marine boundary layer at Fukushima is estimated at 2 x 10^5 [atoms / m^3], 365 times above expected natural background concentrations. Model calculations imply that 0.7 percent of the total radioactive sulfate present at the marine boundary layer at Fukushima reached Southern California as a result of the trans-Pacific transport [18].

DEBRIS BEDS COOLING

INTRODUCTION

A debris bed as a mixture of fuel debris submerged in a pool of water was formed as a result of the Three Mile Island core damage accident.

Since the decay of the fission products could evaporate the water, it becomes of paramount importance to continue cooling these debris beds in the case of an accident, whenever possible. If cooled, remelting of the fuel debris can be avoided.

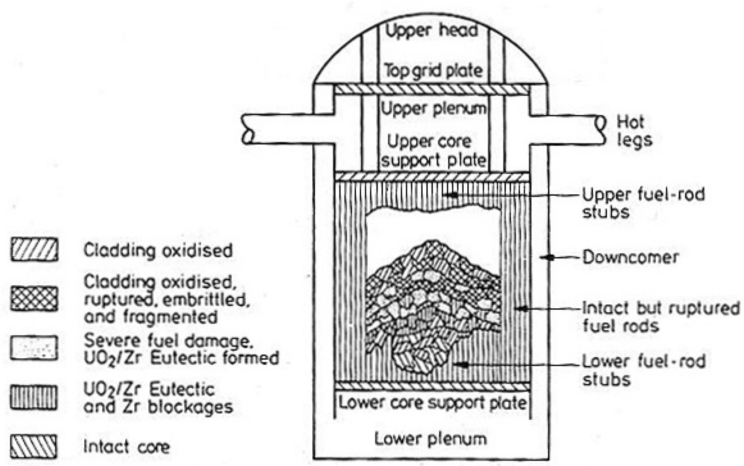

Figure 43. Debris bed resulting from the core damage in the Three Miles Island accident.

The cooling of the debris beds is a complex process and is affected by many factors including the composition of the debris and their particle size.

It also depends on the dimensions of the bed, the operating pressure, the coolant availability and the method of access to the debris bed. Different situations present themselves, demanding different approaches to their cooling.

SHALLOW BED “CHIMNEYS” COOLING

In the case of the existence of a shallow bed of immersed particles at the bottom of the containment, “chimneys” form much like in the case of those forming in rice when cooking. The formed steam escapes through the chimneys. The liquid is pulled through capillary action through the particulates layer in between the chimneys. This efficient method of cooling can only exist under a very limited set of conditions.

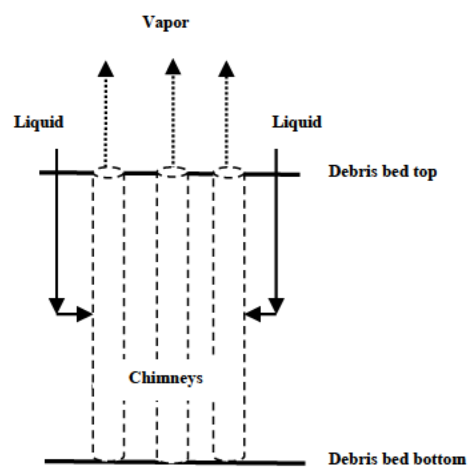

Figure 44. Debris bed chimneys cooling.

CLOSED DEEP BEDS COOLING

In this case the cooling liquid enters from the top of the debris bed. It trickles down the debris bed and cools it. It generates vapor which escapes from the top of the bed.

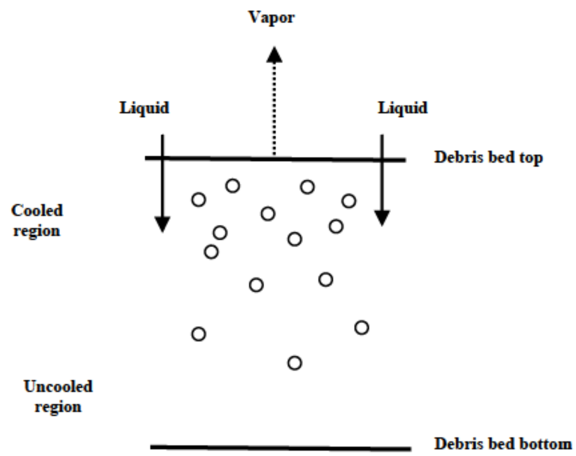

Figure 45. Closed bed debris bed cooling.

The situation causes a flooding phenomenon with the generated vapor countering the flow of the liquid and resulting in only the top of the bed being effectively cooled; a case of steam-binding.

Without cooling, the bottom part of the debris bed would overheat. The overheating of the bottom of the bed is more severe the smaller the particle sizes in the bed. Drying out of the bottom may occur, followed by melting and fusing of the particles, limiting the cooling capability.

ONCE-THROUGH MULTILAYERED COOLING

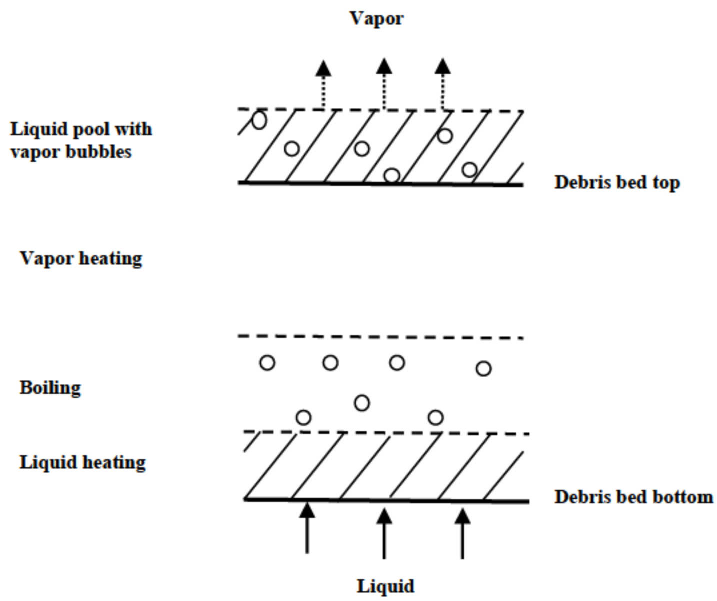

Figure 46. Multilayered once-through debris bed cooling.

This is the best possible situation where the cooling liquid reaches the bottom of the bed and flows upwards through it through the action of forced and natural convection, much like what occurs in a steam boiler.

The natural convection would be caused by the differential in density of the fluid within and outside the debris bed.

The debris bed could be the subject of a pressure drop within the primary system that would drive the flow.

The decay heat generated within the fission products would bring the fluid coolant to its boiling point generating vapor bubbles. As the fluid moves through the bed, it is totally converted into vapor. At this stage, the temperature rises rapidly up the bed.

If the circulation is insufficient, or the debris bed is too thick, the particles at the bottom of the bed could rise to a high enough temperature so that they fuse together, eventually obstructing the upward flow.

EXPERIMENTAL OBSERVATIONS

The debris bed cooling efficiency is dependent on the particles size. In the case of deep debris beds cooling, at atmospheric pressure, for a 1 m deep bed with particles 4 mm in diameter, a heat dissipation rate of 750 kW/m^3 is achievable. On the other hand, if the particle size is 0.1 mm in diameter, the heat dissipation rate falls dramatically to the 20 kW/m^3 level.

A typical debris bed can have a decay heat power generation rate from the fission products of 1 MW/m^3 about 3 hr after an accident. This is the time at which, should cooling of the core fails, the core would melt down in a PWR accident. This bed could be dissipated in a bed 0.5 m in thickness if the particle size is larger than 2 mm in diameter.

The real difficulty here is that the size of the particles varies as the accident progresses, and it is difficult to predict their sizes. Thus the worst case scenario must be envisioned by providing a method of spreading the bed into a well cooled pool in the case of an accident.

This provision is used in the newer Evolutionary PWR, EPWR design by the French Company Areva, where the corium material is spread into a well confined shallow pool that would cool itself passively through radiative cooling to the atmosphere.

EFFECT OF N^{16} FORMATION

In light water and heavy water moderated and cooled reactors, the threshold fast neutron activation set of reactions with the isotopes of oxygen in the water:

$$\begin{aligned} &{}_8O^{16} + {}_0n^1 \rightarrow {}_1H^1 + {}_7N^{16} \\ &{}_7N^{16} \rightarrow {}_8O^{16} + {}_{-1}e^0 + \gamma \end{aligned} \tag{17}$$

with: $T_{1/2}\left({}_7N^{16}\right) = 7.1 \text{ sec}$,

E_γ = 6.13, 7.11 MeV in 69 percent of the decays,

$\sigma_{activation}$ = 46 mb,

abundance of ${}_8O^{16}$ = 99.758 percent,

$\rho(H_2O) = 1.0\ [gm/cm^3]$

and the set of reactions:

$$\begin{aligned} &{}_8O^{17} + {}_0n^1 \rightarrow {}_1H^1 + {}_7N^{17} \\ &{}_7N^{17} \rightarrow {}_8O^{17*} + {}_{-1}e^0 + \gamma \\ &{}_8O^{17*} \rightarrow {}_8O^{16} + {}_0n^1 \end{aligned} \tag{18}$$

with: $T_{1/2}\left({}_7N^{17}\right) = 4.17 \text{ sec}$,

$\sigma_{activation}$ = 5.9 mb,

abundance of ${}_8O^{17}$ = 0.038 percent,

* denotes an excited state,

are significant, particularly in the Boiling Water Reactor (BWR), because of the short transit time of the generated steam between the reactor core and the turbine and other equipment external to the reactor shield.

As N^{16} decays into O^{16}, the latter can interact with the Zr cladding generating Zr oxide.

In addition, some radiolytic decomposition of the water produces O^{16} and free H, which are both available for chemical interaction.

CASUALTIES

Two Tepco employees at the site were conducting regular checks when the earthquake hit on March 11, 2011. They apparently ran into a basement turbine room where they likely drowned as the tsunami swept over the plant.

Two workers of a contractor or cooperative firm were injured by the earthquake, and were hospitalized.

One Tepco employee with suspected heart condition hospitalized. One subcontractor worker became unconscious and was hospitalized.

Radiation exposure of one Tepco employee working inside the reactor building, exceeded an effective dose of 10 cSv or 10 rem and was hospitalized.

Two Tepco employees on duty in the central control rooms of Unit 1 and 2 wearing full radiation protection attire, were transferred to Fukushima Daini Power Station for medical consultation.

Four workers were injured and hospitalized after the explosion in Unit 1. Four Tepco employees and 2 contractors workers hospitalized after the unit 2 explosion.

On March 24th, 2011 it was confirmed that 3 workers from the cooperative companies who were in charge of cable laying work in the 1st floor and the underground floor of the turbine building were exposed to the radiation dose equivalent of more than 17 cSv or rem. Two of them were confirmed with skin contamination on their legs. After they were decontaminated, since there was a possibility of beta particles burn injury, they were transferred to the Fukushima Medical University Hospital. The third worker was also transferred to Fukushima Medical University Hospital on March 25th, 2011. Later, the 3 workers were transferred to the National Institute of Radiological Sciences in the Chiba Prefecture for monitoring. They all left the hospital on March 28th, 2011.

Six workers may have received in the recovery effort an effective dose exceeding the government's annual limit of 25 cSv or rem for occupational workers, bringing the total to eight who have exceeded the limit. Two of the workers may have received double that limit. The findings are based on a preliminary assessment of 2,367 of 3,726 people who worked at the plant in March, 2011.

AFTERMATH

Figure 47. Cleanup of the March 11, 2011 earthquake and tsunami at the town of Rikuzentataka, Japan.

With alternate sources of cooling provided to the affected plants, the situation would get better by the day. However, significant damage did occur. Eventually, the heat generation will subside as the damaged fuel disperses in the coolant water, collapses and forms a debris bed, burns itself out and is starved of too much water to cause it to reach a critical configuration. A critical configuration needs an optimal fuel to moderator ratio, optimal surface to volume ratio, and the absence of neutron absorbing elements to exist.

The now suspected existing debris beds in the damaged reactors cores and the damaged fuel in the spent fuel storage pools will eventually shut themselves down to the condition that happened in nature at the Oklo natural reactors which shut themselves down after being starved of the moderating action of water by Earth movement.

Figure 48. Aftermath of Fukushima Daiichi accident on March 18, 2011, one week after the accident. Rubble from hydrogen explosions in units 1, 3 and 4 and fire in unit 3 is spread over the site. Damage from earthquake and tsunami to the electrical systems apparent along the water front. Steam still emanating from unit 2. Source: DigitalGlobe.

A lesson to be learned from the Oklo natural reactors is that starving a chain reaction from water as a moderator and adding neutron non-moderating absorbing materials such as boron, lithium, sand, gravel and iron pebbles would eventually extinguish it.

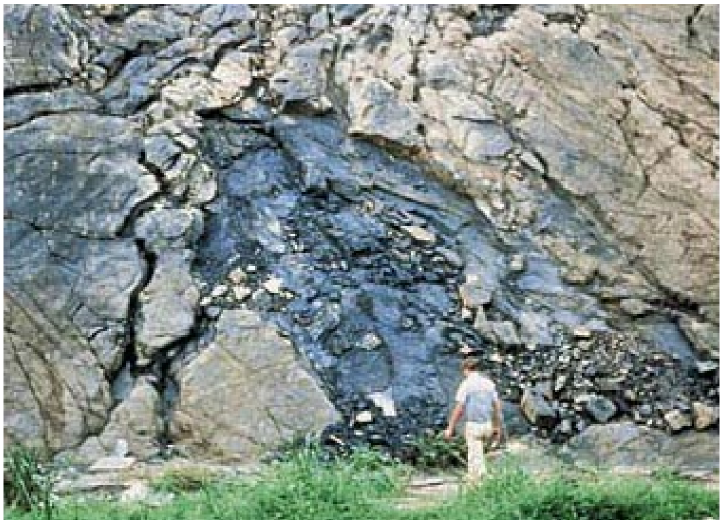

Figure 49. Outcrop of a natural reactor zone at the Oklo Phenomenon site. With water absent as a moderator, the chain reaction was starved and shut down.

The damaged reactors at the Fukushima site would have to be prevented from leaking radioactivity to the environment trough the effects of wind and rain by surrounding them initially with an enclosure like the one used at the Chernobyl site, until the decay of the radioactivity would allow them to be dismantled for ultimate disposal.

Figure 50. Encased damaged reactor at the Chernobyl site.

Figure 51. Encasing the Fukushima reactors.

INTERNATIONAL NUCLEAR AND RADIOLOGICAL EVENT SCALE, INES

The International Atomic Energy Agency, IAEA initially rated the accident as a level 4 out of 7 on the scale of international nuclear accidents, and then upgraded it to the 5 level; “accident with wider consequence.”

The Windscale and Three-Mile-Island events were rated at 5, and the Chernobyl event at 7. The cascading failures and involvement of multiple units is a unique feature of the Fukushima event.

The Fukushima accident involved fuel damage and releases of fission products such as I^{131} and I^{132} which the Three Mile Island accident did not. It appears more serious in its consequences than the Three Mile Island Accident. For this reason, the French authorities unofficially consider it at the 6 level.

On April 12, 2007, Japan’s Nuclear and Industrial Safety Agency, NISA, raised the accident rating to the level 7. The International Nuclear and Radiological Events Scale, INES runs from zero to 7 as a major accident.

Table 9. INES scale rating of some nuclear incidents.

INES level	Event	Description
1	Mihama, Japan, 2004	Hot water and steam leakage from broken pipe. No radiation release.

		Five casualties, 7 injuries.
4	Tokaimura, Japan, 1999	Nuclear processing facility. Workers mix larger than indicated materials in buckets, breaking safety rules. Criticality accident occurred. Two workers casualties. Fourty injured workers receive treatment.
5	Three Mile Accident, USA, 1986	Small-break Loss of Coolant Accident in unit 2. Fuel and core damage. Minor radioactive release. No casualties. Unit 1 continues operation.
5	Windscale, Sellafield, UK, 1957	Fire in graphite reactor core. Release of radioactivity. Sale of milk restricted for a month period. Reactor enclosed in concrete. Site decontaminated. New reactors built on the site.
6	Mayak, Kyshtym, Chelyabinsk, USSR, 1957	Fault in cooling system. Chemical explosion in waste tank. Radioactive release of 70-80 tonnes. Contamination of surrounding area.
7	Chernobyl, Ukraine, 1986	Core criticality, fire in graphite core, steam explosion in one of four reactors. Fire burns for 9 days. Two casualties in steam explosion and 47 first responders from radioactive exposure. Radioactive release.
7	Fukushima, Japan, 2011	Station Blackout caused by earthquake and tsunami damage. Hydrogen and possible steam explosions, fires and fuel damage. Four units out of six at site decommissioned. Radioactive release.

The normal background radiation from cosmic and terrestrial radiation absorbed dose rate is around the 80 nGy/hr range. Some surrounding cities recorded dose rate readings in the range 1,213-3,024 nGy/hr. For comparison, an abdominal x-ray is associated with an absorbed dose (not dose rate) of 1 mGy or 1,000 nGy.

The radiation dose equivalent rate has stabilized to 500 μSv/hr or 0.05 cSv/hr or 0.05 rem/hr on site. Notice that for gamma rays, the radiation quality factor Q = 1, and accordingly the Gray unit for absorbed dose and Sievert unit for the effective dose become equivalent. Also note that 1 cSv = 1 rem.

Some workers are reported to have been exposed to an effective dose or dose equivalent of 100 mSv or 10 cSv or 10 rem. The maximum allowable occupational dose rate in the USA is 5 rem / (year.person) or an average of 2 rem/yr averaged over 5 years. The maximum allowable dose equivalent rate to a member of the public at large is 170 mrem / (year.person) compared with that from the natural radiation background of about 220 mrem / (year.person).

Soon after the disaster Japan's health ministry raised the maximum radiation level to which each worker can safely be exposed from 10 cSv/yr or rem/yr to 25 cSv or rem/yr to enable them to spend more time in contaminated areas.

As of April 1st, 2011, Nisa said that 21 workers had been exposed to radiation exceeding 10 cSv, although tests have shown that no one has been exposed to radiation high enough to damage their health.

About 19,000 people were thought dead or missing from the earthquake and tsunami event. More than 166,200 lived in shelters on high ground above the vast plains of mud-covered debris.

The cost of the damage is about $433 billion or 300 billion euros, making it the world's costliest natural disaster after the 1995 Kobe earthquake in Japan which cost $100 billion and hurricane Katrina in the USA in 2005 that caused $81 billion in damage.

DECOMMISSIONING

The Toshiba Corporation proposed to the Tokyo Electric Power Company (Tepco) and to the Ministry of Economy Trade and Industry (Meti) to decommission the four damaged reactors at the Fukushima Daiichi nuclear power plant. The proposal involved Toshiba's Westinghouse Electric Company division, the Babcock & Wilcox Company and the Shaw Group, who gained experience in the cleanup of the Three Mile Island accident in 1979.

This sets out to level damaged buildings and structures at the Fukushima Daiichi complex without causing any more contamination to leak and will utilize robots to remove radioactive rubble caused by the hydrogen explosions and the earthquake and tsunami that affected the facility on March 11, 2011.

It will take about 10 years to remove the nuclear fuel rods and spent rods in the storage pools from the four reactors and improve the condition of soil contaminated by any radiation leaks. The Hitachi Company with the General Electric Company and the Bechtel Corporation could also be involved.

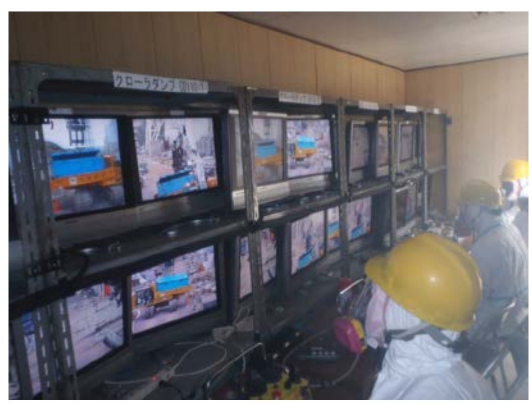

Figure 52. Removal of debris using remote control equipment and autonomous transporters. A useful design feature at the Fukushima site is an emergency command control center in an earthquake proof bunker with power supplies, radiation shielding thick walls, communication gear, food and water supplies and two air filtration systems. Source: Tepco.

Figure 53. Unmanned Aerial Vehicle, UAV T-Hawk MAV by Honeywell pictures of tops of units 1 (top), 3 (middle) and 4 (bottom), as of April 10, 2011. Source: Tepco, Honeywell.

Figure 54. Damage below the fuel storage pool in unit 4 as seen from the ground on March 22, 2011. Water being pumped into the damaged spent fuel pool using a boom. Source: Tepco.

DECONTAMINATION AND REMEDIATION



Figure 55. Storage tanks for sludge resulting from the water decontamination process and coolant storage tanks, June 10, 2011. Source: Tepco, DPA.

Most of the water poured for cooling the reactors overflowed or leaked into basements, connecting tunnels and service trenches at the plant. The Tepco electrical utility with the help of Areva from France and Kurion from the USA installed a water decontamination system that uses ion exchange resins and Zeolite filters. By the end of the year it expects to have generated 2,000 m^3 of sludge separated from the water used to maintain cooling of the units.

The sludge will be initially stored in tanks at the station site then moved to a temporary storage unit in December 2011. About 105 x 10^6 liters or 28 x 10^6 gallons of contaminated water lies in basements and trenches. About 10,000 m^3 of water were discharged to the ocean.

The activity in the contaminated water is estimated at 0.72 x 10^{18} Becquerels or 19 x 10^6 Curies, almost as much as the activity released into the atmosphere in the five days after March 11, 2011, according to Japan’s Nuclear and Industrial Safety Agency, Nisa. In comparison, at Chernobyl, 5.2 x 10^{18} Becquerels or 193 x 10^6 Curies of activity was released.

LESSONS LEARNED, REACTIONS TO FUKUSHIMA ACCIDENT

Nuclear plants operators all over the world have actively reviewed their safety policies and procedures as a result of the Fukushima accident. The occurrence of cascading failures in multiple reactor units is unprecedented and generates concerns about the existence of faulty emergency procedures, the presence of design flaws, or both.

In August 2011, the Japanese cabinet transferred the country's nuclear safety agency from the trade ministry as a department dedicated to the expansion of nuclear power, to the environment ministry. Japan separated regulation of the nuclear industry from promotion.

Reviews of the established emergency procedures and the operational safety of existing and planned plants were initiated in Germany, China, Switzerland, Italy, Belgium, the UK and the USA. In the USA, concern centered around the Peach Bottom plant at Delta, Pennsylvania, operated by the Exelon utility company that uses a GE design similar to the four damaged units at the Fukushima Daiichi site.

FLOODING HAZARD

In contrast to Tsunami events, flooding events can be predicted weeks ahead of time allowing mitigation and safety measures to be implemented ahead of time.

The flooding as a result of the tsunami of the pumping and electrical components below grade level in the turbine plant and other reactor buildings was a contributing factor to the accident sequence of events. This implies that other causes of flooding, such as river overflow or snow melt, merit renewed scrutiny as possible initiating events of similar accident sequences in both BWRs and PWRs and other facilities worldwide.

As it becomes realized that the flooding by the tsunami of the pumping equipment in the turbine hall and other buildings basements were a contributing factor in the accident sequence of events, then that situation should be considered in emergency planning for reactors in inland areas that would be prone to other forms of flooding events, even though river flooding events give a longer advance warning period than a tsunami to implement protection measures. On the other hand, they can last a longer stretch of time as rain or snow melt can continue feeding the flow of a river system for an extended time period.

Cooper Station Flooding Event, July 1993

Figure 56. Cooper Station, Brownsville, Nebraska on the Missouri River flooding event, 1993.

The Nebraska Public District’s Cooper Station, Brownsville, Nebraska on the Missouri River sustained a flooding event in July 1993 when upstream dikes and levees failed and suggested a shutdown of the plant. The below grade levels in the turbine hall and reactor building had water accumulation when the floor drain system backed up. The rising water level affected the electrical cabling and equipment including the Reactor Core Isolation Cooling (RCIC) pump room causing them to be shorted out.

Fort Calhoun Flooding Event, June 2011

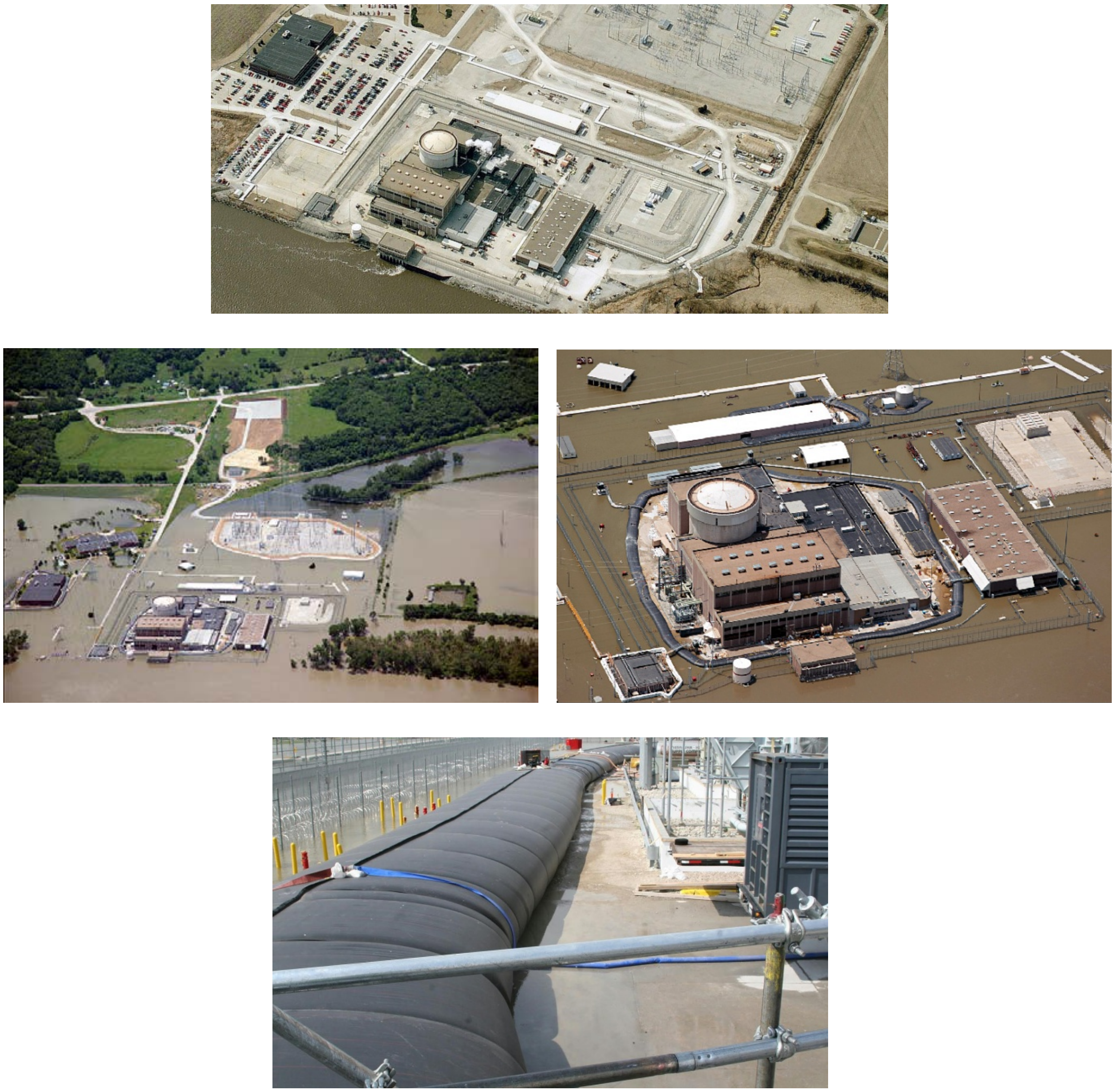

Figure 57. Fort Calhoun station, Blaine, Nebraska, 19 miles north of Omaha on the Missouri River is protected against flooding by a 2,000-ft long Aqua Dam berm from releases from the Gavins Point Dam, June 10, 2011. The berm raises the protection 6 ft above the 1,004 ft river level to the 1,010 ft Mean Sea Level, MSL. Source: OPPD.

Figure 58. Fort Calhoun's Aqua dam, June 26, 2011. Source: ABC News.

Figure 59. Circuit breaker 345 kV at transformer substation protected with sandbags and walking bridges around buildings were implemented against flooding at Fort Calhoun, Nebraska, June 13, 2011. Source: OPPD.

In the USA, Nebraska's Fort Calhoun Station, operated by the Omaha Public Power District (OPPD), 19 miles north of Omaha, Nebraska is one of three plants in the USA facing the highest level of regulatory scrutiny because the plant's safety systems were found in 2010 to be in danger of flooding. The plant is designed to accommodate a water level of 1,007 ft above Mean Sea Level (MSL) before any additional barriers are added. River flooding from snow melt and spring rains is a common occurrence in the Mississippi-Missouri Valley area of the USA particularly when the La Ninã weather event is prevalent. Nuclear Regulatory Commission, NRC inspectors reported that the plant, located on the Missouri River, did not have enough sand to fill bags that operators planned to place on a flood wall to protect buildings and equipment. The flood wall plan violation was considered as a "substantial" safety risk.

Heavy rainfall and snowpack runoff led in the spring of 2011 to flooding of the Missouri River Basin that is the most severe the region since the 1950-1960s. The river water level was expected to rise 5-7 ft above flood stage in much of Nebraska and Iowa and as much as 10 ft in parts of Missouri. The flooding was expected to last into August because of heavy spring rains in the Upper Plains and a substantial Rocky Mountains snow pack melting into the Missouri River basin.

The Fort Calhoun plant was in cold shut down status for refueling since April 2011, as it was surrounded by flood waters caused by a release of 150,000 ft^3 / sec from the Gavins Point Dam raising the Missouri River 5-7 feet above flood stage in Nebraska and Iowa. The river rose 1.5 ft above Fort Calhoun's 1,004 ft elevation above MSL.

At 8:00 am on June 6, 2011 a Licensee Emergency Classification as "Notification of Unusual Event (NOUE)" or "Preliminary Notification of Event of Unusual Occurrence (PNO-IV-11-003) was issued in anticipation that the Missouri River level at the plant would reach 1,004 ft Mean Sea Level (MSL) in the next two days. The river level was about 1,003.2 ft in MSL. The USA Army Corps of Engineers (USACE) projected the river to crest at 1006.6 ft MSL within 10 days, with persistence within the month of July and possibly beyond.

At 9:40 am CDT on June 7, 2011, the plant raised the classification to an "Alert" to the USNRC Region IV staff at Arlington, Texas, (PNO-IV-004-A) following a fire in a switchgear room. The fire suppression system in this switchgear room operated as designed and the fire was quickly extinguished, but briefly knocked out power to two pumps circulating water in the spent fuel pool. Temperatures in the spent fuel pool increased a few degrees but remained at safe levels and the plant remained shutdown through the event, and exited the alert mode at 1:15 pm on June 7, 2011 into a normal response mode.

A controversy aroused when a report by Russia's Federal Atomic Agency (FAEE) reportedly based on data provided to it by the International Atomic Energy Agency (IAEA) suggested that the plant suffered a "catastrophic loss of cooling" to one of its idle spent fuel pools on June 7, 2011 and that reading were made of "negligible releases of nuclear gases." Under the guidelines of the International Nuclear and Radiological Event Scale (INES) this would be an "accident with local consequences," making it a "Level 4" emergency on the INES scale. This coincided with remarks days earlier by the USA Nuclear Regulatory Commission (USNRC) Head Gregory B. Jaczko acknowledging that: "the policy of not enforcing most fire code violations at dozens of nuclear plants is 'unacceptable' and has tied up the hand of NRC inspectors."

As the level of the Missouri River continued to rise, news media helicopters circled the area. This prompted Omaha Public Power District (OPPD) officials to contact the Federal Aviation Administration (FAA) with a request that they remind pilots of the Notice To Airmen (NOTAM), in effect since September 11, 2001, restricting the airspace around the plant. Other NOTAMS have remained in effect since then for all of the nuclear power plants in the USA, as well as other elements of the critical infrastructure such as oil refineries. This suggested that matters were much worse than officials were publicly admitting, spurring false reports that the airspace over the plant had been closed because of a more serious situation.

The emergency diesel generators remained primed to come into action if a loss of offsite power became imminent with enough diesel fuel stockpiled to run the plant cooling for a month. The generators were hardened in flood protected bunkers. Provisions were made for resupply if necessary by reinforcing surrounding levees and raising the level of railroad tracks accessing the site. An extra diesel generator was made available and the electrical switchyard was protected with a berm to a height of 1,011 ft.

Other plants facing flood threats include the Exelon Corporation's Quad Cities plant, Cordova, Illinois, as well as the NextEra Energy's Duane Arnold BWR plant at Hiawatha, Iowa. The Robinson Steam Electric Plant in Hartsville, South Carolina and the Wolf Creek Generating Station in Burlington, Kansas have received NRC scrutiny.

Redundant safety systems, backup power supplies and several methods for shutting down reactors are used at USA plants. Most plants get their electricity from two or three high-power grid lines. If those should fail, two sets of backup diesel generators come on automatically and are housed in buildings designed to withstand tornadoes, fires, earthquakes, floods and tsunamis. Should the power lines and generators all fail, every plant has the ability to run its systems on batteries for 8-12 hours while another generator is brought in or the power lines are repaired.

RETIRING AND REPLACING AGING FLEETS OF NUCLEAR POWER PLANTS

GERMANY'S DEINDUSTRIALISATION

Aging fleets of nuclear power plants are expected to be retired, to be replaced with newer inherently safe designs. In Europe, Germany, Switzerland and Italy reached a decision to gradually phase out their aging fleet of nuclear power plants. Meanwhile, the construction and planning of new units continues elsewhere in the world.

Table 10. Forecast hurdle facing implementation of renewable sources of energy in Germany.

Renewable Source	2010 [TW.hr/year]	2030 [TW.hr/year]
Biomass	31.7	56.1
Hydropower	20.4	23.5
Wind Power	43.4	182
Solar Energy	12.5	57
Geothermal		6.6
European Union Energy Network		35.4
Share of power generation	18 percent	66 percent

Germany's nuclear reactors generate about 25 percent of its electricity. The concern following the Fukushima accident led to a drastic decision by the authorities in Germany to initially impose a three-months moratorium by "state-decree" on an extension of the operating licenses of their 7 oldest nuclear units built before 1980, pending a review of their operational safety. The Krümmel reactor near Hamburg, Germany that went into operation in 1984 may be decommissioned. Germany would be left with 9 aging operating reactors. In 2010, Germany had extended the operating licenses of its fleet of 17 reactors by an average of 12 years. Eight out of Germany's 17 reactors may end up being decommissioned by the end of 2011.

Figure 60. Control rod drives at the bottom of the Krümmel BWR reactor near Hamburg, Germany that went into operation in 1984.

On May 31, 2011, Germany decided to shut down 8 of its 17 aging reactor fleet, and to retire the remaining 9 successively by the end of 2022. This would increase Germany’s dependence on wind, solar, biofuel and on lignite or brown coal. A side effect is that Germany would fail to reach its emission control goal of CO_2 reduction by 40 percent relative to 1990, since lignite is cheaper than natural gas. Europe would need to increase its imports of coal by 20 percent. This would be associated with a tough effort to achieve a decrease in energy use by 10 percent by 2020. In addition, the investment in a new power grid to accommodate the renewable source would result in higher energy costs. This could also lead to a process of gradual deindustrialization of Germany with its industrial sector leaving it to neighboring countries with cheaper energy sources.

The decision entails a risk of 161 deaths / TW.hr from coal-produced electrical energy, versus 0.04 for nuclear electricity. An estimate by Deutsche Bank is that the decision would result in the release of 400 million extra tons of CO_2 by 2020. Germany hopes to achieve its goal by increasing efficiency of buildings by renovating them with insulation in walls and double glazing windows, and by ramping up renewable energy. Some doubt whether Germany's energy needs can be met by renewable energy sources, so it positions itself as an experiment in energy sources substitution.

In 2011, by 2022 Germany’s plan would be to decommission all of its nuclear power plants, and by 2050, 80 percent of all energy in the country should come from renewable sources. It is a grandiose plan that heralds an era of offshore wind farms, solar panels and wind turbines across large parts of the country and pumped-storage hydroelectric plants that would ensure a constant flow of electricity even when the wind is not blowing and the sun is not shining.

By 2012 after the bold announcement, little progress has happened, except for painful price hikes that have hit consumers' pocketbooks and companies' bottom lines. Many offshore wind farms are not connected to the grid yet, and the massive power masts needed to transport the energy have not been built. Norbert Röttgen, the person in charge of implementing the highly ambitious clean energy plans was fired for his lack of progress on the difficult energy project.

The aspect of the energy policy that has drawn the greatest criticism, is the fact that it has been accompanied by higher electricity prices for companies and consumers alike. Energy prices have been rising steadily since the introduction of Merkel's policy, and Germany's largest steelmaker, ThyssenKrupp, even blamed the policies for the sale of one of its steel mills, which is to be closed. European Energy Commissioner Günther Oettinger warned: "High electricity prices have already initiated deindustrialization in Germany."

The pressure created by the shutdown of Germany's remaining 8 nuclear power plants over the next nine years is immense and counterproductive -- because it will drive up electricity prices. The energy turnaround cannot be allowed to make electricity so expensive that factories are forced to close and people lose their jobs. The energy turnaround cannot become so expensive that the average family must pay €100 ($126) a month for electricity alone. One year after Germany decided to phase out nuclear energy, all hopes that a turn toward a future of renewables could be ordered from above have proven to be illusory. The project is the greatest current challenge facing the country.

The problem, first and foremost, is a fundamental misunderstanding of German energy policy. Where Germans get their electricity -- whether from natural gas, coal, sun or wind -- is not the product of political decisions but of the market economy. Companies do not base their decision to build a power plant on some ambitious political project but on profitability. Whether solar panels continue to be installed is not purely a function of government subsidies but also of price. And the question of the power grid is big enough also depends on citizens, who also have a say; many people may find the energy revolution super in theory but don't want a power pylon in front of their living room window. The more concrete the energy transition becomes, the larger the problems appear: faltering grids, near electrical blackouts, enormous costs, and the growing role of state interference in the market economy [19].

EUROPEAN COUNTRIES RESPONSE

Switzerland's five operational reactors will remain in operation until the end of their lifespan with the last one being decommissioned in 2034. Nuclear energy provides about 40 percent of Switzerland's energy, which Switzerland states will be met by increased renewable energy.

Following the Chernobyl accident in 1987, Italy decided to shut down its four nuclear power plants. The last operating plant closed in 1990. The decision was reversed in 2008. After the Fukushima event, Italy announced a one-year moratorium on its plans for new nuclear power plants by 2014. A referendum in June 2011 expressed opposition to the plans as well as water privatization.

The European Union (EU) agreed to carry out stress tests on all 143 nuclear plants in the bloc. The plants that fail the tests could be expected to be decommissioned. In March 2011, the EU published its report: “Roadmap for Moving to a Competitive Low-Carbon Economy by 2050,” outlining how the EU could reduce its greenhouse gas emissions 80-95 percent by 2050 based on 1990 levels. In order to reach this goal, the EU identified three key factors: improving energy efficiency; investing in the energy market to create a zero carbon infrastructure by investing in the development of renewable energy, such wind and solar, and by ensuring European continent-wide electricity grid interconnections.

JAPAN’S EXPERIENCE

The ambition to increase the electrical share of nuclear electricity in Japan from 29 to 50 percent faces serious hurdles. The emphasis could be redirected towards replacing existing aging plants with new plant designs benefiting from accumulated knowledge and advanced passive and inherent safety technologies and designs. Japan is considering increasing the share of electricity production from renewable sources, particularly from solar photovoltaic farms, from the present 10 to 20 percent by 2020. It is considering a framework which makes the power business open for anyone who has the will to start it by having access to its power grid, currently controlled by 10 regional utility monopolies, and by an obligation by the utilities to accommodate the ventures and purchase the produced energy.

Reforms would have to strip the power distribution function from the utilities monopolies and separate the power production, transmission and distribution businesses. Energy is a very high cash-flow business similar to the telecommunication one, and deregulation and end of monopolies would invigorate it by allowing new entrants developing new sources and technologies. Japan would have to cut the cost of solar power generation to 1/3 current levels by 2020 and 1/6 by 2030 by depending on a distributed system of photovoltaic solar panels placed on roof tops. High hopes are placed on thin-film solar cells technology. The new directions would determine the future of Japan’s industrial competitiveness much like they will affect Germany’s.

GLOBAL RESPONSE

From a different perspective, in the 2009 Copenhagen Summit the global efforts to control climate change could punish countries that do not include noncarbon-based energy sources in their power mix. In May 2011, the UN's scientific body, the Intergovernmental Panel on Climate Change (IPCC), released study suggesting that 80 percent of the world's energy needs could be met through renewable energy sources by 2050. A UK review recommended that Nuclear Electricity remain as a part of a future non-carbon energy mix.

Nuclear energy will still be needed globally as part of the energy mix as a non-carbon source replacing the depleting hydrocarbon sources. The Kingdom of Saudi Arabia is a case in point. According to a royal decree in April 2010: “The development of atomic energy is essential to meet the kingdom’s growing requirements for energy to generate electricity, produce desalinated water and reduce reliance on depleting hydrocarbon resources.” Saudi Arabia, experiencing a 6-8 percent annual growth in electricity demand, needs 60,000 MWe of added electrical capacity by 2020. In June 2011, it unveiled plans to build 16 nuclear power plants by 2030 at a cost of $100 billion for electricity and fresh water desalination. It realized that its depleting hydrocarbon resources would be placed into better uses generating export revenue for its economy rather than meeting the domestic electricity needs.

TECHNICAL IMPROVEMENTS AND MODIFICATIONS

The pressure suppression loss at the Daiini unit 2 should have been averted since the plant is reported to have had off-site power available to it.

A review of the effect of the core spray system in BWRs regarding fuel damage and hydrogen generation is warranted. The placement of critical electrical and mechanical components in zones of the plant that are prone to be flooded must be reconsidered. The design of the seals of the control rod drives that could cause leakage from the bottom of the pressure vessels of corium material and then cooling water must be reviewed. The sources of common-mode failures such as the redirecting of the steam-hydrogen mixture from the unit 3 plant to unit 4 causing a fire and hydrogen explosion in an otherwise shutdown unit is a faulty procedure.

Most of the radioactive release from the accident was caused in the fire that occurred in the unit 4 reactor that was shutdown at the time of the earthquake-tsunami. This directs attention towards the reconsideration of the practice of storing spent fuel in storage tanks at the reactor sites.

Reactors at the Fukushima Daiini site were able to recover once the connection to the grid was re-established, whereas those at the Daiichi were not because of earthquake damage to the transformer station connecting it to the grid. This suggests the need for multiple independent grid connections. Alternatively, other sources of electrical energy such as solar and wind could be made available in the vicinity of the plant with adequate forms of energy storage such as batteries, flywheels or other methods.

The loss of cooling in the fuel storage pools could have been caused by leakage of the water from the gates in the pools used for fuel transfer. Their behavior under seismic activity may need detailed investigation.

The reported fire in the fuel storage pool needs careful examination as to its causes and progression. Some pool designs use a Boral spacer of the fuel assemblies in the spent fuel storage pool. The use of Boral as a shielding material needs further analysis. Boral is a shielding material with boron carbide (B_4C) embedded in an aluminum matrix. If oxygen is available from the heat and radiation dissociation of the water, aluminum is combustible at high temperatures. In fact, a mixture of powdered aluminum and iron oxide is used as a solid rocket fuel and was used as coating on the Hindenburg dirigible.

The need for passive cooling designs has been recognized and implemented in newer designs. The chimney effect is used to advantage in the ABWR and the ESBWR, with the latter depending solely on natural circulation convection cooling.

A suggested more favorable location for the pressure suppression pool is above the reactor core. This offers the benefit of providing passive natural circulation convection cooling of the core, upon equalizing the pressure between the core and the pressure suppression pool, without the need for active pumping requiring off-site or on-site power supplies in addition to operator intervention subject to human error. Reactors with the design feature of the pressure suppression pool positioned below the core could be replaced with more advanced designs providing passive convection cooling in the core itself or with a pressure suppression pool positioned above the core.

It is not yet clear what the role of the core spray system in the Fukushima accident has been. The timing of the initiation of the core spray system needs a renewed theoretical and experimental analysis. It is clear that the core spray system would cool the fuel elements upon core uncovery if their temperature has not reached a critical level. But beyond a certain temperature level the spraying of the hot cladding would generate steam with possible oxidation of the cladding and hydrogen production. If the source of water is initially relatively cold from the condensate storage tank, thermal stresses would also be expected leading to cladding damage.

The deterministic and probabilistic safety analyses of postulated reactor accidents complement each other. In a deterministic safety analysis emphasis, the maximum historical magnitude earthquake or tsunami wave height at the reactor site, become the emphasis as stipulated for the Fukushima reactors site. The probabilistic analysis of different magnitude earthquake or tsunamis may have not been sufficiently emphasized in Japan as is the case in the USA.

The probabilistic and possibilistic consideration of earthquakes and tsunami events as "common mode failure" events may have been underestimated by their consideration as independent events. Another common-mode failure was caused by the hydrogen produced in the fuel damage of unit 3 flowing through a gas treatment line into unit 4 through damaged valves. The hydrogen leaked through ducts on the 2nd, 3rd and 4th floors and caused a fire and explosion in an otherwise shutdown unit.

USA REVIEW OF REACTOR SAFETY

The USA Nuclear Regulatory Commission (USNRC) issued in March 2012 three rules to improve the safety levels at the nation's 104 operating reactors. The rules include a requirement for nuclear plants owned by electrical utilities such as Exelon Corporation and Entergy Corporation to have a plan to indefinitely survive station blackouts. Reactor operators also must have adequate instruments to monitor the spent-fuel cooling pools. Another order calls for older reactors with General Electric Company (GE) design containment structures to have sturdier hydrogen venting systems to prevent damage to reactor cores.

The new the rules, which must be implemented by 2016, are exempt from an agency cost-benefit analysis, though future regulations may not be. A potential requirement for some reactor containments to have filtered vents to prevent radiation leaks may not be as cost-effective as additional pumps and safety valves. The nuclear industry has already begun to implement a plan to install commercial-grade gear, including portable pumps and generators at plants to provide an additional layer of safety.

The orders take effect immediately, and the agency is also weighing a dozen recommendations from a task force to prevent a disaster similar to Fukushima from occurring at USA plants.

USA FLEXIBLE AND DIVERSE, FLEX STRATEGY RESPONSE TO EXTREME NATURAL EVENTS

Reactor operators in the USA have agreed, as part of an industry plan, to install emergency equipment at power plants. The order on equipment for station blackouts mitigation calls for a phased-in approach, with power plants initially using portable equipment to keep reactors cool during an electric failure, supplemented by gear that can be shipped in to sustain those functions indefinitely.

The Nuclear Energy Institute, a Washington-based industry group representing 27 nuclear utilities, plant designers, architect engineering firms and fuel cycle companies, offered a plan in December 2012 that USNRC officials said helped to speed the regulatory process. The industry spent about $100 million to buy and install emergency equipment, including pumps and generators, at power plants.

The equipment would be used if other systems that comprise a facility's multi-layered safety strategy are compromised. The additional equipment is a key element of the industry's "flexible and diverse" or FLEX strategy developed in response to the Japan's Fukushima Daiichi accident.

The equipment that has been acquired or ordered under FLEX includes: diesel-driven pumps, air-driven pumps for flood equipment, sump pumps, hoses, electric generators, battery chargers, electrical switchgear, fittings, cables, fire trucks, satellite communications gear and also support materials for emergency responders. Although each nuclear power plant has multiple safety systems designed specifically for that facility, the FLEX initiative provides another layer of safety as part of a nuclear power plant's response capability to extreme natural events. The new equipment will be stored at diverse locations and protected to ensure that it can be used, if necessary, following extreme natural phenomena such as earthquakes, floods, hurricanes or tornadoes that are applicable to a specific site.

The portable equipment will provide additional means of power and water to maintain three key safety functions in the absence of electrical power and heat transfer capability from permanently installed safety systems: reactor core cooling, used fuel pool cooling and containment integrity.

JAPAN'S NUCLEAR ENERGY FUTURE

The earthquake and following tsunami on Friday, March 11, 2011 claimed the lives of about 20,000 people. Initially, 52 of the country's 54 reactors were shut down, being subjected to stress tests and safety modifications before being allowed to be restarted. They faced opposition by Japan's rural prefectures local governments. The construction of 14 additional nuclear power plants by 2030 was shelved. The share of nuclear electricity in 2011 of 29 percent was reduced in 2012 to about 2 percent, subjecting Japan as the world's third largest industrial nation to an unprecedented energy shortage and crisis, and lead to a negative balance of payments for its economy.

New legislation that would limit the operation of old nuclear power plants to their initial design lifetime of 40 years was enacted. Measures for the reduction of energy consumption were implemented with fines to firms that exceed their assigned quotas. Energy providers restarted decommissioned oil and gas power plants. Ten of these aged plants had to be temporarily shut down due to malfunctions. Companies such as Nippon Steel and paper-maker Oji ran their plants partly with their own generators. A number of firms began feeding surplus energy into the public power grid in competition with regional monopolies, such as the Tokyo Electrical Power Company (Tepco). Tepco, facing compensation losses of several trillion yen, faced the threat of being nationalized.

Japan was forced to import Liquefied Natural Gas (LNG) to replace the required fuel needed for its gas turbine electrical plants. Japan's Institute for Energy Economics, suggested that LNG could only meet 2/3 of the country's energy requirements if all its nuclear power plants were shut down. The imports of LNG and crude oil drove Japan's trade deficit to a record high. Buying and importing those fuels triggered the threat of higher electricity bills.

After a long and arduous series of routine inspections, as well as many power failures and blackouts, Japan resumed in April 2012 the restarting of its shut-down nuclear power plants when Prime Minister Yoshihiko Noda declared that two reactors were already safe to reactivate and operate after having passed stringent stress tests. This vote of confidence suggests that demand for nuclear energy will continue to exist in Japan. The first units to be reactivated were the number 3 and 4 units at Kansai Electric Power's Ohi plant, in time to face a summer power demand peak. By May 15, 2012, officials in the Japanese town of Ohi have approved the restart of the two nuclear power reactors in the Fukui prefecture. After a briefing from the central government and Kansai Electric Power Co., the Ohi assembly agreed that restarting the reactors is necessary to maintain jobs and the town's finances.

Also in May, Japan's National Federation of Small Business Associations asked the government to restart the nation's nuclear reactors to stabilize the power supply. The association told Industry Minister Yukio Edano that an increase in electricity rates would devastate small businesses.

Lacking in domestic energy resources, Japan does not appear prepared to downsize its economy and forego a modern industrial society and is compelled to move ahead with the restart of its nuclear industry better equipped with emergency provisions to face unforeseen natural events.

DISCUSSION

About 20 percent of nuclear reactors in the world operate at the vicinity of tectonically active zones. The construction of new power plants in tectonically active zones around the Pacific Ring of Fire and in the Middle East region is expected to come under intense review as to the necessary implementation into them of passive rather than active safety measures as exists in the currently considered designs.

A renewed emphasis on the development of renewable wind, solar, geothermal, tidal and bioenergy sources will likely occur for a few years. Along that time the inevitability and the need for nuclear power in the energy mix will be even more recognized for base load generation replacing the depleting fossil fuels and their carbon emissions.

As a result of an earlier earthquake-caused accident at the Tepco Kashiwasaki-Kariwa plant in July 2007, emphasis has been placed on protecting reactors components from earthquake events. The plant automatically shut down and was adequately cooled in spite of a leakage of water containing a minor quantity of radioactive material that was released to the ocean without causing harm to humans or the environment.

Worldwide, the need to replace aging nuclear power plants by newer inherently safe and passive technology may have been deemphasized under economical pressures to extend the life of existing plants. Brought into operation on March 26, 1971, the Fukushima BWR unit 1 had an age of 40 years; at the end of its initial design lifetime. A nuclear power plant is usually granted in the USA an operational license for 20 years with a built-in extension of another 20 years for a total of 40 years if the safety level of the plant is deemed favorable.

The affected unit 1 reactor was due to be retired in February 2011, but its license was extended for another 10 years beyond its initial 40 years operational time after a safety review and upgrades. In the USA licenses for operating plants are being extended by 20 years beyond their 40 years licenses to 60 years based on a detailed review of their safety operational level. Most of the components such as the steam generators have been replaced or renovated under these license extensions, except for the pressure vessels.

Minuscule amounts of fission products I^{131} and Xe^{133} circulated the globe and were detected on March 27, 2011 at Nevada, USA, without causing any health risks.

Earthquakes are a way of life in Japan, occurring once every 5 minutes on average. Structures are built to withstand Earth movements. It is recognized that the human toll of about 16,000 and 3,000 missing was tragically caused by the combined earthquake and tsunami events; definitely not by the reactor accident. It can be argued that the Fukushima Daiichi site accident, as caused by the earthquake-tsunami occurrence, was a "beyond-design-basis" accident. A Tepco official in fact called it "sotegai" or "outside our imagination."

Richard K. Lester at MIT observed that the year 2011 is the 100th anniversary of the discovery of the atomic nucleus:

> "In historical terms, that puts the field of nuclear engineering today roughly where electrical engineering was in 1900. The creation of the electric power grid, television and telecommunications could not have been anticipated by the electrical engineers of 1900. Likewise, no one today can foresee the future of nuclear energy technology. All that can be said with confidence now is that the nuclear power plants of the year 2100 will have about as much resemblance to today's; as a modern automobile has to a 1911 Model T. New materials and systems are being developed all the time to make nuclear safer. The need for intellectual vitality, flexibility and creativity has never been greater."

Engineers and scientists worldwide will be spending the next 7 lean years in the history of nuclear power redefining the safe use of nuclear energy and addressing and solving the issues uncovered by the Fukushima accident. Among others:

1. The role of the inner core spray in hydrogen generation accidents,
2. Corium leakage from control rod seals in BWRs,
3. The suspected steam explosion at Fukushima unit 3,
4. Flooding as a new accident classification,
5. Alternate emplacement of electrical and safety equipment in reactor architectures,
6. Cooling of spent fuel pools enclosures,
7. The consideration of common-mode failures in safety analyses,
8. Aging issues in operational power plants.

Historically, among other natural and man-made causes, this event would have tested the courage, endurance, resilience and tenacity of the 127 million people of Japan, who under adversity have always recovered, rebuilt and thrived.

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REFERENCES

1. Norman J. McCormick, "Reliability and Risk Analysis, Methods and Nuclear Power Applications," Academic Press, 1981.
2. R. T. Lahey, Jr. and F. J. Moody, "The Thermal-Hydraulics of a Boiling Water Nuclear Reactor," ANS/AEC Monograph Series on Nuclear Science and Technology, The Division of

Technical Information, United States Energy Research and Development Administration, American Nuclear Society, 1977.
3. M. Ragheb, O. Uluyol, B. G. Jones (Univ. of Illinois), S. A. Ho, and R. Endicott (PSE&G, Hancocks Bridge), "Station Blackout Simulation Model for a BWR Plant," Accident Analysis, Trans. Am. Nucl. Soc., Vol. 62, pp. 362-364, November 11-15, 1990.
4. M. Ragheb, A. Ikonomopoulos, and B. G. Jones, S. A. Ho, and R. Endicott, "Best Estimate Analysis of Station-Blackout for a PWR Plant," Joint Relap5 and Trac-BWR International User Seminar, Idaho National Engineering Laboratory and Commonwealth Edison Company, pp. 117-122, September 17-21, 1990.
5. M. Ragheb, A. Ikonomopoulos, B. G. Jones (Univ. of Illinois), S. A. Ho, R. Endicott (PSE&G, Hancocks Bridge), "Best-Estimate Analysis of a Small-Break Loss-of-Coolant Accident for a PWR Plant," Accident Analysis, Trans. Am. Nucl. Soc., Vol. 62, pp. 358-360, November 11-15, 1990.
6. M. Ragheb, A. Ikonomopoulos, B. G. Jones, S. A. Ho, R. Endicott, "Best Estimate Analysis of Complete Loss of Normal Feedwater without Reactor Scram for a PWR Plant," Power Plants Transients," The American Society of Mechanical Engineers, FED-Vol. 104, pp. 117-122, November 25-30, 1990.
7. L. Tsoukalas, G. W. Lee, M. Ragheb, T. McDonough, F. Niziolek and M. Parker, "On-line Model-Based System for Nuclear Plant Monitoring," Applications of Artificial Intelligence VII, Proc. of SPIE-The International Society of Optical Engineering, Vol. 1095, pp. 372-380, 1989.
8. Tokyo Electrical Power Company, Tepco, http://www.tepco.co.jp/en/index-e.html , March 2011.
9. M. Ragheb, "Boiling Water Reactors," Nuclear, Plasma and Radiation Science. Inventing the Future, https://netfiles.uiuc.edu/mragheb/www/NPRE%20402%20ME%20405%20Nuclear%20Power%20Engineering/Boiling%20Water%20Reactors.pdf , 2011.
10. M. Ragheb, "Containment Structures," Probabilistic. Possibilistic and Deterministic Safety Analysis. Nuclear Applications, https://netfiles.uiuc.edu/mragheb/www/NPRE%20457%20CSE%20462%20Safety%20Analysis%20of%20Nuclear%20Reactor%20Systems/Containment%20Structures.pdf , 2011.
11. M. Ragheb, "Steam Explosions," Probabilistic. Possibilistic and Deterministic Safety Analysis. Nuclear Applications, https://netfiles.uiuc.edu/mragheb/www/NPRE%20457%20CSE%20462%20Safety%20Analysis%20of%20Nuclear%20Reactor%20Systems/Steam%20Explosions.pdf , 2011.
12. M. Ragheb, "Decay Heat Generation in Fission Reactors," Probabilistic. Possibilistic and Deterministic Safety Analysis. Nuclear Applications, https://netfiles.uiuc.edu/mragheb/www/NPRE%20457%20CSE%20462%20Safety%20Analysis%20of%20Nuclear%20Reactor%20Systems/Decay%20Heat%20generation%20in%20Fission%20Reactors.pdf, 2011.
13. M. Ragheb, "Debris Bed Cooling," Probabilistic. Possibilistic and Deterministic Safety Analysis. Nuclear Applications, https://netfiles.uiuc.edu/mragheb/www/NPRE%20457%20CSE%20462%20Safety%20Analysis%20of%20Nuclear%20Reactor%20Systems/Debris%20Beds%20Cooling.pdf, 2011.
14. M. Ragheb, "Natural Nuclear Reactors, The Oklo Phenomenon," Nuclear, Plasma and Radiation Science. Inventing the Future," https://netfiles.uiuc.edu/mragheb/www/NPRE%20402%20ME%20405%20Nuclear%20Power%

20Engineering/Natural%20%20Nuclear%20Reactors,%20The%20Oklo%20Phenomenon.pdf , 2011.
15. M. Ragheb, "Management of Radioactive Waste," Nuclear, Plasma and Radiation Science. Inventing the Future," https://netfiles.uiuc.edu/mragheb/www/NPRE%20402%20ME%20405%20Nuclear%20Power%20Engineering/Management%20of%20Radiooactive%20Waste.pdf , 2011.
16. M. Ragheb, "Chernobyl Accident," Probabilistic. Possibilistic and Deterministic Safety Analysis. Nuclear Applications, https://netfiles.uiuc.edu/mragheb/www/NPRE%20402%20ME%20405%20Nuclear%20Power%20Engineering/Chernobyl%20Accident.pdf , 2011.
17. M. Ragheb, "Stationary Low-Power Plant Number 1, SL-1 Accident," Probabilistic, Possibilistic and Deterministic Safety Analysis. Nuclear Applications, https://netfiles.uiuc.edu/mragheb/www/NPRE%20457%20CSE%20462%20Safety%20Analysis%20of%20Nuclear%20Reactor%20Systems/Stationary%20Low%20Power%20Plant%20Number%201%20SL1%20Accident.pdf , 2011.
18. Antra Priyadarshi, Gerardo Dominguez, and Mark H. Thiemens, "Evidence of neutron leakage at the Fukushima Nuclear Plant from Measurements of Radioactive S^{35} in California," Proceedings of the National Academy of Sciences, http://www.pnas.org/content/early/2011/08/11/1109449108, August 15, 2011.
19. Daryl Lindsey, "Merkel Faces 'Herculean Task' on Green Energy," Der Spiegel, May 24, 2012.