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Station Blackout Accident at Fukushima

SAFETY

An analysis of the phenomenology of the earthquake and tsunami-induced station blackout accident at the Fukushima Daiichi plant, Japan and its consequences, is attempted. 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 under 4.2 m of water. The pressure vessels of units 2 and 3 are likely to be damaged and leaking water from their bottoms. 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, was averted by judicious supplemental cooling. The implications of the accident are discussed.

Por el **el DR. MAGDI RAGHEB,** Departamento de Ingeniería Nuclear, de Plasma y Radiológica, Universidad de Illinois, Campus de Urbana-Champaign, 216 Talbot Laboratory, 104 South Wright Street, Urbana, Illinois 61801, EE.UU. https://netfiles.uiuc.edu/www/mragheb
mragheb@illinois.edu

Figure 1. Station Blackout loss of power to the control room of the Fukushima Daiichi unit 1 reactor on March 24, 2011 (left). Restoring offsite power to units 1 and 2 and power to the control room of unit 2 on March 26, 2011

Introduction

Japan generates 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 include 24 Pressurized Water Reactors (PWRs), 30 Boiling Water Reactors (BWRs), and 2 under construction.

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 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. Eighteen-foot high offshore breakwaters offered protection against typhoons, but apparently, not tsunamis. 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. 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 event in Japan since the start of historical record-keeping in the 1800s.

Eathquake Magnitude and Strength

Magnitude Scale

Referred-to in Japan as “san ten ichi ichi” or 3/11, the earthquake is estimated to have involved 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 energy release is thus equivalent to about 480,000 / 20 = 24,000 such devices. As a result of the enormous energy release, 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:

(1)

$$\Delta M = \log_{10} \frac{M_2}{M_1} = \log_{10} M_2 - \log_{10} M_1$$

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

(2)

$$e^{\ln x} = 10^{\log_{10} x} = x$$

$$\frac{M_2}{M_1} = 10^{\log_{10} \frac{M_2}{M_1}} = 10^{\Delta M}$$

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

(3)

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

This implies that the ratio between the design M_1 and the experienced M_2 earthquakes on the magnitude scale is a factor of:

(right). The hanging ceiling tiles resulted from the earthquake. Source: Tepco.

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

$$\frac{M_2}{M_1} = 10^{(9.0-8.6)} = 10^{0.4} = 2.5$$

Strength, Energy Release, Destructiveness

The magnitude scale compares the recorded amplitudes of waves on a seismograph and does not directly describe the magnitude of the energy release from an earthquake. The energy release is what affects structures and causes the damage they incur. To estimate the energy release E, an empirical formula is usually used that relates it to the magnitude M as:

(3)

$$\log_{10} E \;\; \alpha_\ell \;\; 1.5M$$

The energy release or strength can be estimated from:

(4)

$$10^{\log_{10} E} \;\; \alpha_\ell \;\; 10^{1.5M}$$
$$E \;\; \alpha_\ell \;\; 10^{1.5M}$$

From which:

(5)

$$\frac{E_2}{E_1} = \frac{10^{1.5M_2}}{10^{1.5M_1}} = 10^{1.5(M_2-M_1)}$$

The ratio between the strengths or energy release E_2 of the incurred 9M earthquake to the design 8.6M earthquake E_1 can be estimated as::

$$\frac{E_2}{E_1} = \frac{(10^{1.5})^{9.0}}{(10^{1.5})^{8.6}} = 10^{(1.5)^{9.0-8.6}} = 10^{(1.5)^{0.4}} = 10^{1.176} = 14.99; 15$$

The actual earthquake was hence 15 times the strength of the design earthquake and hence destructiveness. Large earthquakes evidently have much larger strength or energy release factors than small ones and are hence are much more devastating.

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 off-site 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 following sequence of photos were taken from the 4th floor of the waste processing building at the power plant. They were shot over the course of a minute and reveal how quickly the tsunami inundated the area. Source: TEPCO

The earthquake triggered a safe shutdown of the three fission chain reaction of the 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 remained unavailable to the plant.

The Kobe earthquake, in 1995, had a local magnitude of 7,2 points on the Richter scale, and caused 6.400 deaths.

Emergency Core Cooling System, ECCS

Because of the shutting 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 became 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 available 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's 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 shut down for maintenance purposes, and 3 others were inside and outside the enclosure of unit 6 which was also offline for servicing.

Figure 7. Spent fuel storage pools (top) showing fuel assembly being moved through gate between pool and reactor top. Yellow object is removed core dome. Steam emanating from the fuel storage pool in unit 4 on March 15, 2011, under the loading crane showing at the center of the picture (bottom).

Upon arrival 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 4.2 m in one turbine building. This disabled 12 of the 13 emergency diesel generators and affected their associated electrical switching gear as the sea water shorted the electrical circuits. Within an hour after the earthquake 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."

Figure 8. Highly energetic vertically propagating hydrogen or possibly steam explosion at the Fukushima Daichi unit 3 BWR on March 14, 2011 was followed by a fire and suspected 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 pressure vessel can be inferred

> *hasta ahora no se había producido ninguna sucesión de fallos semejantes en dos instalaciones y con varias unidades de reactores afectadas simultáneamente tras un accidente por apagón total*

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 and control 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 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 as designed. Nuclear power plants differ from other heat engines in that after shutting down the chain reaction, the fission products resulting from the fission of 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,” “afterheat,” or “afterglow heat,” needs to be extracted and rejected until it has decayed within days to a level that does not need active cooling any more.

Under normal conditions, the excess heat in a BWR is rejected by bleeding steam from the steam lines and is quenched in the main condensers 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 the mere pumping of 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 RHR 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.

Loss of Reactor Core Isolation Cooling System, RCIC

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 from the control system, 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 Reactor 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

from the absence of the reactor’s top plug in the ejecta. Source: NTV / NNN Japan.

The earthquake and subsequent tsunami which affected the japanese coast in march, having caused thousands of deaths and missing people, is considered economically the most expensive disaster in history.

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 operation of the Low Pressure Coolant Injection, LPCI system with a low head but large flow rate to adequately cool the fuel in the core.

Main Steam Isolation Valves, MSIVs

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

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

Main steam line flow restrictors of the venturi 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.

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.

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 radioactivity from the NSSS.

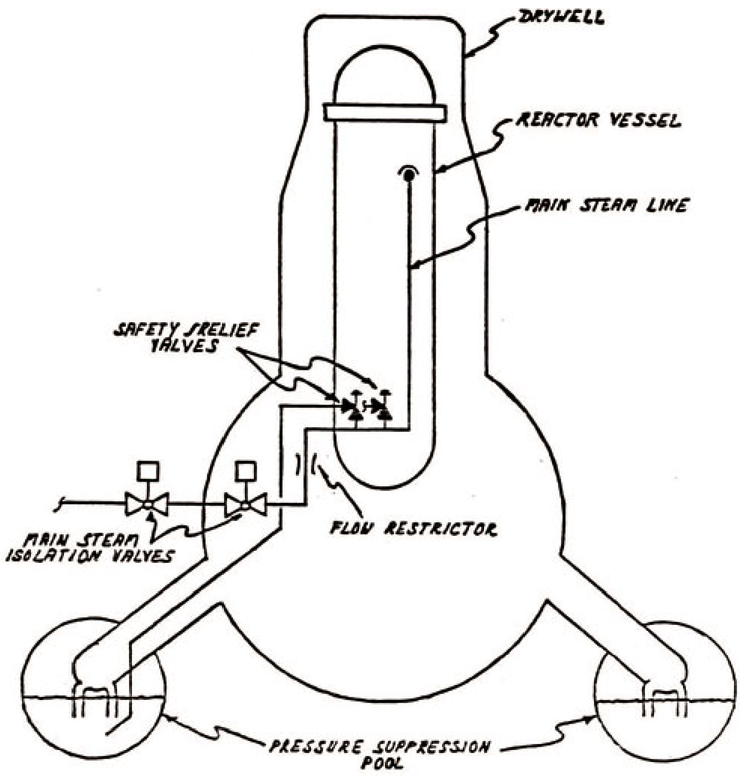

Figure 3. Main isolation valves and safety relief valves used in the depressurization of a BWR plant. Source: GE.

Depressurization, Steam Venting

As no circulation of the core was provided, the water turned into steam uncovering the core. In most BWRs a core spray system would spray the fuel assemblies to cool them. Steam was generated increasing the system's pressure. The safety relief valves automatically 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 noncondensible 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 reportedly damaging its pressure suppression pool. Fuel damage and a partial core meltdown is presumed with some fission products vented. The core had 548 fuel assemblies and the storage fuel pool had 587.

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 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.

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 2^{nd}, 3^{rd} and 4^{th} floors and caused a fire and explosion. 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 release implies cladding oxidation and fuel damage.

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.

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.

A population evacuation and a temporary rolling power blackout were 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.

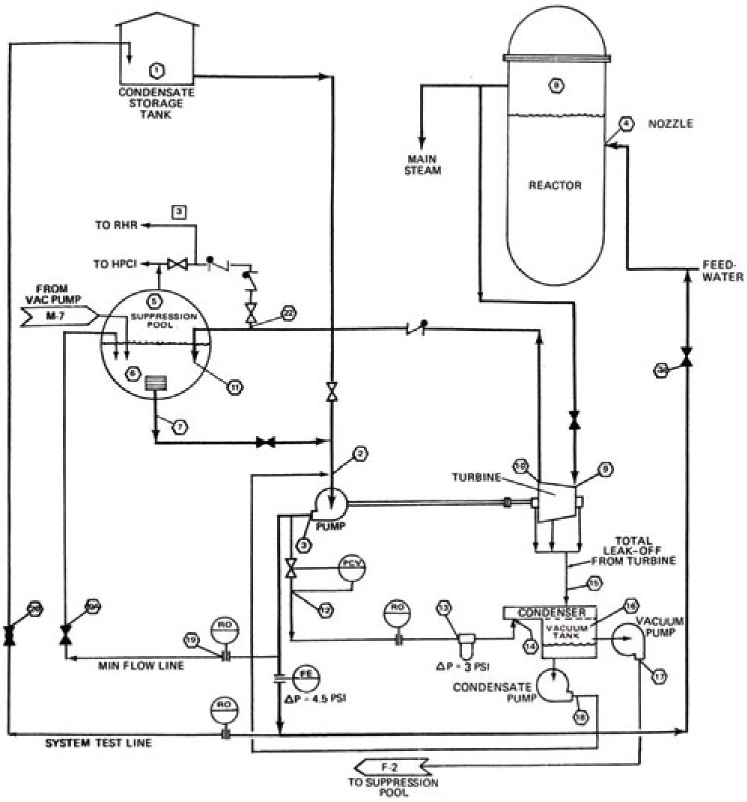

Figure 4. BWR Reactor Core Isolation Cooling system, RCIC. A steam turbine uses steam to drive a pump injecting water drawn from the condensate storage tank into the core. Exhaust from the steam turbine is directed to the pressure suppression pool. HPCI: High Pressure Coolant Injection system, RHR: Residual Heat Removal system. Source: GE.

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 a larger 8.9-9.0M strength one.

The 2004 Sumatra earthquake and tsunami lead to the shutdown of the Kalpakkam nuclear plant near Chennai in India and of 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 claimed the lives 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 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 components in the flooded lower parts in the plant.

On June 17, 2010, the Fukushima unit 2 BWR was scrammed due to a generator problem. Power was lost for a short time 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 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.

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.

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.

The decay heat power ratio is given by [10]:

(6)

$$\frac{P[MWth]}{P_0[MWth]} = 6.48x10^{-3} P_0[t^{-0.2} - (t+T_0)^{-0.2}]$$

where:

- P_0 is reactor fission power before shutdown, MWth,
- P is thermal decay heat power generation, MWth
- t is time after shutdown, 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:

$$\frac{P(t)}{P_0} = 6.48\times10^{-3}[t^{-0.2} - (t+T_0)^{-0.2}]$$
$$= 6.48\times10^{-3}[(\frac{1}{24\times60\times60})^{-0.2} - (\frac{1}{24\times60\times60}+365)^{-0.2}]$$
$$= 0.06094 \approx 6\,\%$$

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 has to be provided.

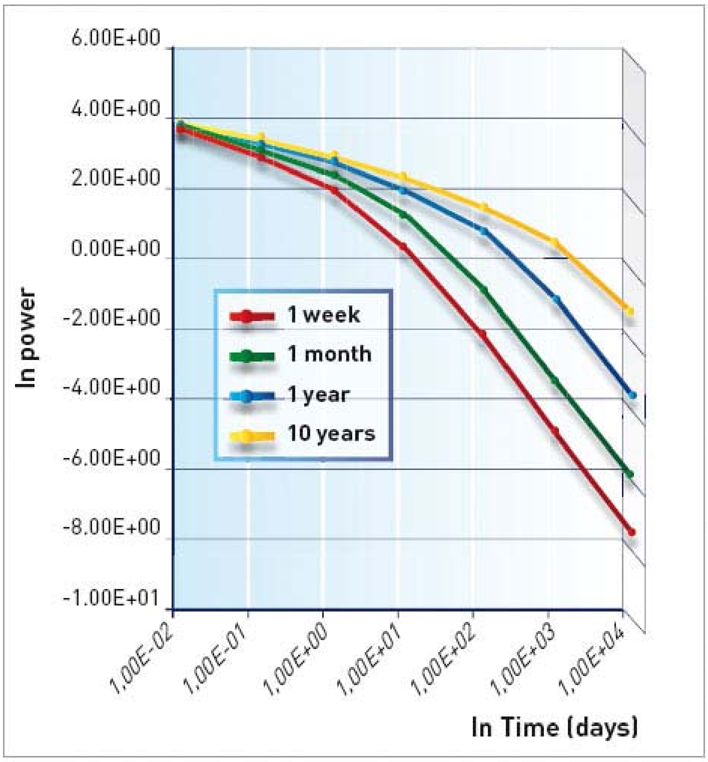

Figure 5. Decay heat power release for a 3,000 MWth Light Water reactor, LWR for different operational times. The decay heat generation power decreases exponentially within a few days after shutdown.

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

$$\frac{P(t)}{P_0} = 6.48\times10^{-3}[t^{-0.2} - (t+T_0)^{-0.2}]$$
$$= 6.48\times10^{-3}[(7)^{-0.2} - (7+365)^{-0.2}]$$
$$= 0.0024 \;\approx 0.24\,\%$$

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

Fission Products Release

The decay heat cooling needs to be actively continued for at least 24-48 hours. If no cooling is provided the fuel Zircaloy 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 place at about 24-48 hours into the accident.

The I^{131} isotope is used 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 concern 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 megawatt thermal of reactor power. The Te^{132} released from a reactor accident will also produce I^{132} outside the reactor according to the reaction:

(7)

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

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

En el caso más grave de daños en el núcleo asociados a altas temperaturas también se pueden liberar productos de fisión menos volátiles, como Cs^{137} y Sr^{90}. 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 also 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 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 $Cs^{o}C$) is considered as moderately volatile and is released only 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 harmless dilution in the vast volume of ocean water.

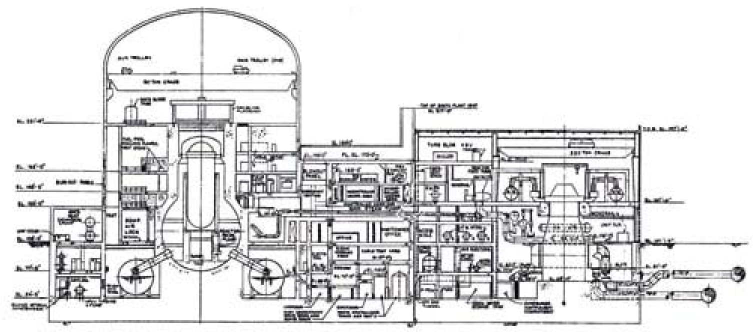

Figure 6. Cutout through containment and turbine hall showing the location of the fuel storage pool in a typical BWR. Components below grade level and hence affected by flooding from the tsunami event include pumps and electrical components. The dry well includes a sump. Any leaking molten corium material through the control rod seals could interact with the sump water as well as the concrete mat causing a steam explosion, then becoming embedded into the concrete. Source: GE.

Hydrogen Explosions

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 zirconium in the cladding interaction:

(8)

$$H_2O + Zr \rightarrow ZrO + H_2$$

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:

(9)

$$2H_2 + O_2 \rightarrow 2H_2O$$

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.

Water suddenly evaporating into steam expands to a large volume. A familiar event is the sudden flashing into steam when the lid 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 postulated 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.

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. 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 at the reactor 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.

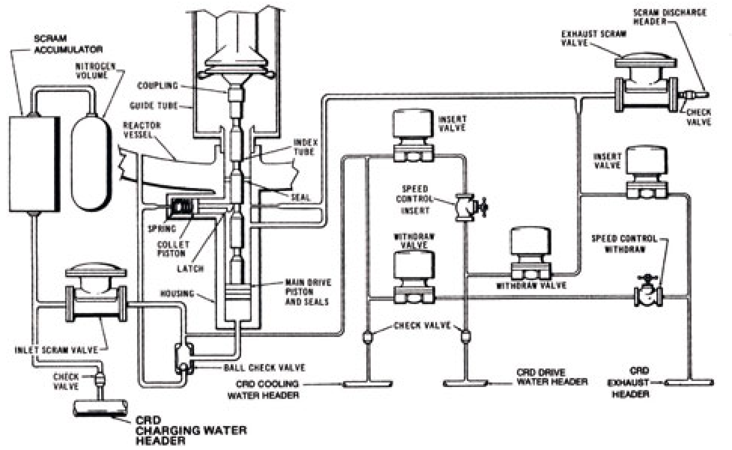

Figure 9. BWR control rod drive mechanism at the bottom of a BWR reactor vessel showing the seal location [2].

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 oF, 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 Mitigation Actions

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 judiciously later extended to 12 miles or 20 km with 170,000 residents.

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. 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.

Emisión de radionúclidos

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.

Table 1. 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}	–	–	$1,0 \times 10^{-2}$	–
	I^{131}	$4,5 \times 10^{-4}$	$8,2 \times 10^{-6}$	$1,0 \times 10^{-3}$	0,4500
	I^{132}	$1,8 \times 10^{-4}$	$1,3 \times 10^{-4}$	$7,0 \times 10^{-2}$	0,0026
	I^{133}	-	-	$5,0 \times 10^{-3}$	-
	Cs^{134}	$1,2 \times 10^{-5}$	$6,4 \times 10^{-6}$	$2,0 \times 10^{-3}$	0,0060
	Cs^{136}	-	-	$1,0 \times 10^{-2}$	-
	Cs^{137}	$1,4 \times 10^{-5}$	$6,2 \times 10^{-6}$	$3,0 \times 10^{-3}$	0,0047
Particulates	Co^{58}	–	–	$1,0 \times 10^{-2}$	-
	I^{131}	$2,1 \times 10^{-4}$	$9,5 \times 10^{-6}$	$1,0 \times 10^{-2}$	0,2100
	I^{132}	-	-	$7,0 \times 10^{-3}$	-
	Cs^{134}	$1,6 \times 10^{-5}$	$8,8 \times 10^{-6}$	$2,0 \times 10^{-3}$	0,0080
	Cs^{136}	-	-	$1,0 \times 10^{-2}$	-
	Cs^{136}	$1,4 \times 10^{-5}$	$9,5 \times 10^{-6}$	$3,0 \times 10^{-3}$	0,0047

Other detected nuclides	Te^{129}	1,6 x 10^{-2}	2,2 x 10^{-2}	4,0 x 10^{-1}	0,0650
	Te^{129m}	1,9 x 10^{-4}	1,5 x 10^{-4}	4,0 x 10^{-3}	0,0475
	Te^{132}	1,2 x 10^{-4}	5,7 x 10^{-6}	7,0 x 10^{-3}	0,0171

Table 2. 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 x 10^{+1}	4,2 x 10^{-2}	4,0 x 10^{-2}	665,8
Cs^{134}	2,062 a	5,6 x 10^{+0}	3,2 x 10^{-2}	6,0 x 10^{-2}	93,8
Cs^{136}	13,10 d	5,6 x 10^{-1}	3,2 x 10^{-2}	3,0 x 10^{-1}	1,9
Cs^{137}	30,17 a	5,7 x 10^{+0}	2,8 x 10^{-2}	9,0 x 10^{-2}	63,5
Ba^{140}	12,79 d	8,8 x 10^{-1}	1,2 x 10^{-1}	3,0 x 10^{-1}	2,9
La^{140}	40,23 h	3,7 x 10^{-1}	8,5 x 10^{-3}	4,0 x 10^{-1}	0,9

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 Cs134 with a 2 years half life, and Cs^{137} with a 30.17 years half life.

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.

Consequences

About 28,000 people were victims of 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 exposure incidents are likely to be identified.

Aftermath

A postulated full core meltdown, in which the molten corium material would melt its way through the pressure vessel, was averted by judicious supplemental cooling. With alternate sources of cooling provided to the affected plants, the situation would get better by the day.

However, significant damage may have occurred. 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.

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 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.

Table 3. 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 to be decommissioned. Radioactive release.

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.

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 reading in the range 1,213-3,024 nSy/hr. For comparison, an abdominal x-ray is associated with an effective absorbed dose (not dose rate) of 1 mSv or 1,000 nSv.

The radiation dose equivalent rate has stabilized at 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 (Gy) unit for the absorbed dose and the Sievert (Sv) 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 a 5 years period. 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 accident, Japan's health ministry temporarily 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 the contaminated areas.
As of April 1st, 2011, Nisa said that 21 workers had been exposed to radiation at levels exceeding 10 cSv or rem, although tests have shown that no one has been exposed to radiation high enough to damage their health.

About 28,000 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, Japan quake which cost $100 billion and hurricane Katrina, USA in 2005 that caused $81 billion in damage.

Conclusions

A postulated full core meltdown, in which the molten corium material would melt its way through the pressure vessel was averted by judicious supplemental cooling.

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.

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.

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 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. Solutions in terms of energy storage to overcome the intermittency nature of wind and solar system will be aggressively pursued. This would include the use of hydrogen as an energy carrier, thermal, flywheel, pumped storage, battery and other storage techniques. 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. The bioenergy approach would cause increased acquisition of land and water resources by capital-rich nations. About 140 million acres of potentially agricultural land have been already acquired in the Sudan and Ethiopia region of Africa for food and fuel production. The food versus energy debate is expected to heat up with possible conflicts about historical water rights such as in the Nile River basin.

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 2^{nd}, 3^{rd} and 4^{th} floors and caused a fire and explosion in a unit that was already shutdown. This design flaw led to a cascading failure event and must be avoided in future designs.

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.

The ambition to increase the electrical share of nuclear electricity in Japan from 30 to 50 percent faces serious hurdles. The emphasis would probably be redirected towards replacing existing aging plants with new plant designs benefiting from accumulated knowledge and advanced passive and inherent safety technologies and designs.

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 concepts, with the latter depending solely on natural circulation convection cooling.

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.

As it becomes established 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 onshore as well as in inland areas that would be prone to other forms of flooding events, such as the Ohio and Mississippi Rivers basins in the USA.

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.

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 notable 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 28,000 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 from MIT offered the insight 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."

- 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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