Chapter 9
The Severe Reactor Accidents of Three Mile Island, Chernobyl, and Fukushima

Abstract Three major severe accidents with core meltdown/core disruption occurred at Three Mile Island (USA) in 1979, Chernobyl (Ukraine) in 1986 and Fukushima (Japan) in 2011.

The LWR of Three Mile Island was a two loop PWR with 880 MW(e) output. The accident started with technical problem in the feedwater loop for the steam generators. As the steam generators were not able to remove the heat, the pressure in the primary system increased and the safety valve of the pressurizer opened thereby releasing steam. The reactor was shut down because of too high pressure. When the pressure in the primary system dropped the safety valve did not shut again and remained open. The operators were given the opposite information by the instruments in the control room. The high pressure emergency core cooling systems started to feed water in the reactor pressure vessel. But the water in the pressure vessel rose too high and the operators throttled the emergency cooling systems. As the primary pumps started to vibrate the operators also shut down both primary pumps. As a consequence the cooling water in the pressure vessel started to boil. The zirconium claddings started to chemically react with water: hydrogen was formed. The reactor core began to melt down. The silver-indium-cadmium control rods did melt. Part of the molten core collected at the bottom of the pressure vessel. A hydrogen explosion occurred in the reactor building. Only the radioactive noble gases and a small part of the fission products iodine and cesium were able to penetrate the filters of the reactor building. The radioactive exposure of the population was therefore very small. Cost for decontamination of the plant and disposal of the destroyed core were very high. The Three Mile Island accident was classified a level 5 accident on the International Nuclear Event Scale (INES).

The Chernobyl accident occurred in one of four RBMK1000 reactors at the Chernobyl site 100 miles north of Kiev. The operators were preparing an experiment in which the energy of rotation of the turbine during shut down should produce emergency electrical power for the support of the diesel generators. Unexpectedly the experiment had to be interrupted for some time to comply with electricity supply which led to the buildup of the fission product Xe-135 (neutron poison). When the experiment could be continued the power level dropped to about

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30 MW(th) because of operator error. This led to additional buildup of Xe-135 (neutron poison). As a consequence the operators had to withdraw the control rods manually to their upper limits after they had shut off the automatic control system. The RBMK1000 was known to have a positive coolant temperature coefficient. This gave rise to instabilities in power production, coolant flow and temperatures in the low power range.

Then the experiment began at the power level of 200 MW(th). Steam to the turbine was shut off. The diesel generators started and picked up loads. The primary coolant pumps also run down. However this led to increased steam formation as the coolant temperature was close to its boiling temperature. With its positive coolant temperature coefficient the RBMK1000 reactor now was on its way to power runaway. When the SCRAM button was pushed the control elements started to run down into the reactor core. However, due to a wrong design of the lower part of the control elements (graphite sections) the displacement of the water by graphite led to an increase of criticality. A steep power increase occurred, the core overheated causing the fuel rods to burst, leading to a large scale steam explosion and hydrogen formation. The reactor core was destroyed and the top shield cover and the fuel refueling machine were lifted up. Fuel elements and graphite blocks were dispersed outside the reactor core. The reactor core was now open to the atmosphere. Fission products and fuel aerosols were distributed over the Ukraine, Belarus, Russia and Europe. Very high radiation doses were received by fire fighters, operators, helicopter pilots and members of the emergency team. Approximately 800,000 military people were involved in rescue teams receiving various levels of high radiation doses. About 135,000 people were evacuated rather late. In total about 3,000 km^2 of land were contaminated with more than 1,500 Bq/m^2, roughly 7,200 km^2 with 600–1,500 Bq/m^2 and about 103,000 km^2 with 40–200 Bq/m^2 of Cs-137. The Chernobyl accident was classified a level 7 accident on the International Nuclear Event Scale (INES).

The severe reactor accidents at Fukushima occurred in 2011 after a severe earthquake with intensity 9 (Richter scale) close to the northeastern coast of Japan. The earthquake was followed by a tsunami wave which hit the six BWRs of the Fukushima-Daiichi plant with a water level up to 14 m. Unfortunately the Fukushima-Daiichi plant was only protected up to a tsunami wave level of 5.7 m. Only three BWRs of the six BWRs of the Fukushima-Daiichi plant were in operation when the earthquake and the tsunami wave hit the reactor site. All BWRs were duly shut down by the seismic instrumentation and changed into the residual heat removal mode. However, the tsunami wave flooded the two diesel generators of each of the three reactor units 1–3, located in the lowest part of the turbine building. The diesel generators and the battery systems failed. The external grid power and heat exchangers transferring afterheat to the ocean water had already been destroyed by the earthquake. In unit 1 due to the lack of electrical power the high pressure coolant injection system did not work. The steam driven isolation condenser system worked only partly in time and failed. The primary coolant system could not be depressurized due to lack of electrical power and pressurized nitrogen. Low pressure emergency pumps, therefore, could not feed water in the primary coolant system. The primary coolant system heated up and exceeded its design pressure. The core became uncovered, the zirconium claddings of the coolant system chemically reacted with water and formed hydrogen. The core melted down. The pressure in the pressure vessel was relieved into the primary containment because core melt penetrated the lower bottom wall. The pressure in the primary containment led to release of hydrogen and fission product gases into the upper reactor building, where a hydrogen explosion occurred destroying the upper building structures.

In units 2 and 3 the accident developed in a similar pattern, though with a larger shift in time. However a hydrogen explosion only occurred in unit 3 (BWR) not in unit 2 (BWR). However, a hydrogen explosion also occurred in unit 4 (BWR) due to a backflow through the common gas treating system. The hydrogen explosion destroyed the upper structures of the reactor building. The spent fuel pools of unit 1, 3 and 4 had to be cooled part time by concrete pumping trucks, water cannons or helicopters dropping water, but no damage occurred to the fuel in the spent fuel pools. After detailed measurements of the radioactivity released into the environment the Japanese government evacuated about 200,000 people. Four persons of the operating crew were killed by the earthquake and the tsunami wave. Some 20 staff members were injured by the hydrogen explosions. Out of the about 23,000 emergency workers 12 received effective radiation doses up to 700 mSv and 75 workers received <200 mSv. The radiation dose of all others was <10 mSv. The contamination of land was measured. About 2,200 persons would not be allowed to return to a no-entry zone because of too high radiation exposure. The Fukushima severe reactor accident was classified level 7 on the International Nuclear Event Scale (INES).

Three major reactor accidents with core meltdown/core disruption occurred at Three Mile Island (TMI), USA, on March 28, 1979; at Chernobyl, Ukraine, on April 26, 1986, and at Fukushima, Japan, on March 11, 2011. The three reactor accidents at Three Miles Island, Chernobyl and Fukushima will be discussed and described briefly below. Prior to the most severe accident at Chernobyl, Ukraine, the reactor accident at Windscale (United Kingdom) in a plutonium production reactor for military purposes in 1957 had been considered the worst nuclear accident with radioactivity release to the environment. It will not be discussed here.

9.1 The Accident at Three Mile Island

On March 28, 1979, a sequence of accidents occurred in unit 2 of the Three Mile Island reactor facility in the United States of America which ultimately resulted in partial meltdown of the reactor core. The pressurized water reactor had been built by Babcock & Wilcox (Fig. 9.1) [1, 2].

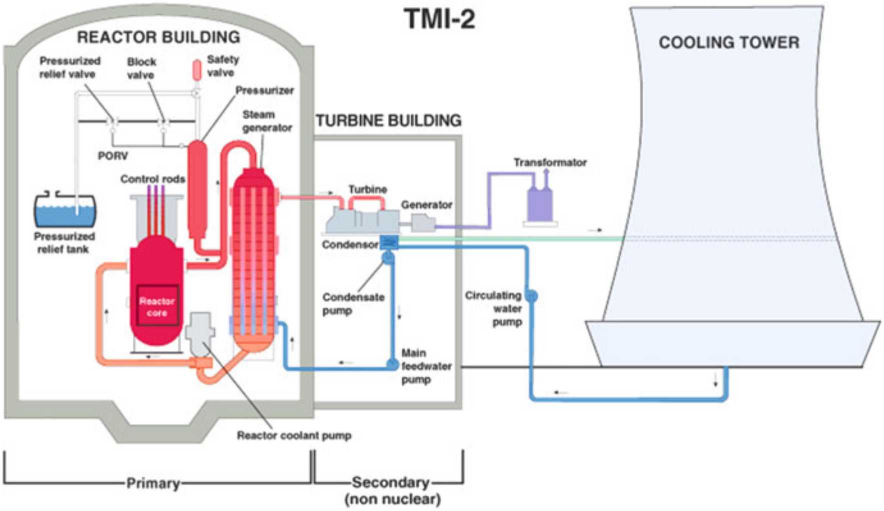


Fig. 9.1 Simplified schematic diagram of unit 2 [1]

It had a reactor power of 880 MW(e) and only two cooling circuits, A and B. The sequence of accidents began with technical problems in the feed water loop for the steam generator. This caused a turbine trip and triggered the startup of the emergency feed water systems. However, the valves in the emergency feed water system were closed by mistake. As the steam generators did not get enough feed water and, for this reason, were not able to remove enough heat, also the temperatures and pressures in the primary cooling circuit started to rise. When an excessively high primary pressure had been reached, the pilot-operated relief valve (PORV) of the pressurizer opened, and the steam was released into the pressure relief tank in the containment. The "primary pressure too high" signal caused the reactor to be shut down. The reactor power dropped to the residual heat level. As a consequence, also the primary pressure dropped. Apart from the mistake mentioned above the events vent on in accordance with the measures planned for that incident condition.

However, the PORV did not shut again at the lower pressure, but remained open. The operators, though, were given the opposite information by the instruments in the control room, namely the indication that the PORV had closed again. The open PORV continued to discharge more steam, and the primary pressure continued to drop. When the primary pressure reached the level at which the high-pressure emergency cooling pumps start to feed, these pumps were activated automatically in order to compensate for the loss of primary coolant. The pressure relief tank was overfilled by the steam released, the water spilled over and collected in the sump of the reactor building. From here it was automatically pumped into storage tanks for radioactive water in the auxiliary systems building (not shown in Fig. 9.1).

The operating crew, who had become confused by the wrong readings of the instruments and did not know precisely the status of the plant, now throttled the high-pressure safety feed system because the water level in the pressure vessel became too high, and opened the valve to a dump pipe. As a consequence of these steps, the water level in the reactor pressure vessel dropped so far that the water coolant began to boil. Although the operating team now succeeded in opening the valves in the feed water line, which had been shut at the beginning of the sequence of accidents, this changed nothing in the further course of the accident.

Roughly 15–30 min after the start of the accident, also the storage tanks filled with radioactive water in the auxiliary systems building started to spill over. Radioactive gases and aerosols entered the atmosphere of the auxiliary systems building. The filters of the auxiliary systems building were able to retain some 99.9 % of the aerosols. But the radioactive noble gases, escaped through to filters to the environment.

As the primary pumps began to vibrate under the impact of steam in the cooling water, the operators first shut down the primary pump of primary cooling circuit B and, slightly later, also that of cooling circuit A. As a consequence, the cooling water in the core began to boil even more violently. The fuel elements, in particular the fuel rod claddings, heated up. At temperatures of the fuel rod claddings above 1,200 °C, steam began to react chemically with the zirconium of the zircaloy cladding, and hydrogen was produced.

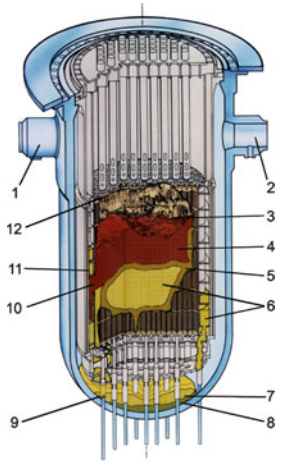
$$Zr + 2\,H_2O \rightarrow ZrO_2 + 2\,H_2.$$

This situation changed only gradually after the operators had created a feed-and-bleed procedure by again feeding water through the high-pressure safety feed systems and bleeding the steam through the open pressure relief system. As late as 15 h after the start of the accident it became possible to restart a primary pump and transfer the reactor into a stable residual heat cooling mode.

The hydrogen produced in the reactor core during the accident entered the reactor building together with the steam, initiating an explosion as a result of self-ignition. As iodine and cesium combined chemically to produce, e.g., CsI, and occurred as aerosols, they were largely retained by the filters in the auxiliary systems building.

The small amounts of aerosols, the shortlived radioactive noble gases, and the gaseous I-131 (halflife 8 days) gave rise to only a relatively low mean radioactive exposure of the population of 0.015 mSv [2] (The world wide annual effective dose caused by natural radiation is about 2.4 mSv/year with a typical range of 1–10 mSv/year in various regions of the world (Chap. 4)). The "Kemeny Committee" appointed by the U.S. President to investigate the Three Mile Island accident arrived at this finding: "The Three Mile Island accident would cause so few cases of cancer, if any, that they would not be detectable statistically" [3].

Analysis of the accident (Fig. 9.2) indicated that roughly one third of the zircaloy fuel rods had reacted with steam and produced hydrogen. When the water of the emergency cooling feed systems contacted the hot fuel rods, this resulted in fragmentation of the zircaloy fuel rod claddings and the UO_2 pellets. The silver-indium-cadmium control rods had molten almost completely. Nearly the entire



1 connection primary line
2 connection primary line
3 cavity built by melt down
4 loose fragments of the core
5 crust of the melt
6 molten material
7 fragments at bottom of spherical calotte
8 uranium depleted region
9 destroyed duct
10 perforated shield
11 layer of molten material on the surfaces of the bypass channels
12 damages at the upper grid

Fig. 9.2 Molten reactor core of the Three Mile Island accident [1, 2]

fission gas plena of the fuel rods had been destroyed, and gaseous fission products had been released. Parts of the reactor core had molten through at the edge of the grid plate and collected at the bottom of the reactor pressure vessel. However, the hemispherical bottom of the pressure vessel did not melt through.

The reactor plant was decontaminated in many years of work, and the reactor top lid was opened. The partly molten reactor core had to be disposed of. Costs amounted to approximately $1 billion [2].

Lessons Learned The non-availability of the emergency feed system, the erroneous signals produced by the instrumentation with regard to the "open" valves of the pressure vessel, and the lack of knowledge of the real status of the plant as well as the shutdown of the primary pumps led to a partial core meltdown.

Present-day pressurized water reactors have better instruments in the reactor pressure vessel and displays in the control room. In addition they have fourfold redundancy of primary cooling and emergency cooling systems, and the possibility to reduce primary and secondary pressures with subsequent possibilities to feed water.

9.2 The Chernobyl Accident

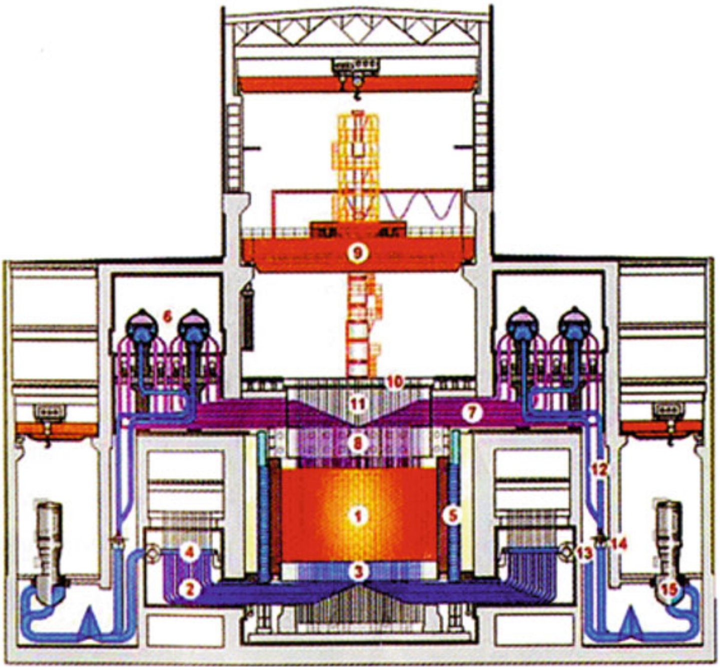
The Chernobyl accident occurred on April 26, 1986 in unit 4 of the reactor plant of four units of 1,000 W(e) or 3,200 MW(th) power each. The four reactor plants had been build some 130 km north of Kiev and comprised four Russian graphite-moderated, boiling-water cooled so-called RBMK1000 reactors. The UO_2 fuel was enriched with 2 % U-235. The core of these RBMK1000 reactors is about 7 m high and about 12 m in diameter. The RBMK1000 has two coolant loops with four circulation pumps each. One pump is always on standby. The reactor core is controlled by raising and lowering 211 control rods. This combination of low-enriched fuel, graphite as the moderator, and boiling water as the coolant resulted in a positive coefficient of coolant temperature (see also Chap. 2) [4–7].

The operators were preparing an experiment in which—after shut down of the reactor- the energy of rotation of the turbine during coastdown was to be used to produce emergency electrical power. This was considered necessary in case of reactor shut down with subsequent failure of the external electrical grid (station black out). The three emergency diesel generators needed about 1 min after their start up to reach full speed and power to feed one primary coolant pump required for cooling of the afterheat generated in the core. This existing lack of emergency power during roughly 1 min was to be provided by the energy of rotation of the turbine during its cast down. Three such experiments had already been carried out 4, 2 and 1 year before the accident, but they had been unsuccessful. They had shown that the excitation voltage of the turbine- generator system was too low. This had been modified in the meantime and the new experiment was to test the new voltage regulation system The experiment was set to begin at a power level at a power level of about 700 MW(th).

The experimental procedures began with a power reduction from full reactor power. However, this had to be interrupted at 1,000 MW(th) because the electrical grid coordinator (load dispatcher) suddenly requested power again. At this point in time, the emergency core cooling systems had already been shut down in preparation of the test. When the load dispatcher permitted again a further drop in power, the envisaged power level was not reached by the operators. During the period of power production at reduced power level the production of the fission products Xe-135 (neutron absorber) had began. It decreased the effective neutron multiplication factor keff and caused the power level to drop to about 500 MW(th). A following operator error (control rods were inserted too far) led to a further drop of power level to about 30 MW(th) [8]. As a consequence, there was additional buildup of the xenon-135 fission product (neutron absorber) with the associated decrease of the effective multiplication factor, k_{eff}. (The amount of Xenon poisoning and its influence on the effective multiplication factor k_{eff} was not known to the operators at that point in time.)

At this very low power level of 30 MW(th) the operators made the decision to restore power by shutting off the automatic control system and to extract the majority of the control rods by manual control to their upper limits. The power started to rise and could be increased to about 200 MW(th), a value smaller than the planned 700 MW(th).

The positive coefficient of coolant temperature of the RBMK1000 reactors was known to cause instabilities in this low power range. When the eight primary coolant pumps were activated during startup, this gave rise to instabilities in power production, coolant flow and temperatures. Various alarms started going off at this time. The operators received emergency signals regarding the levels in the steam/water drums and large variations in the feed water flow as well as from the neutron flux or power monitors, respectively (Fig. 9.3).



1 Reactor core
2 Core inlet pipe
3 Bottom radiation shield
4 Collector – distributor
5 Lateral radiation shield
6 Steam separator
7 Steam-water pipes
8 Top radiation shield
9 Fueling machine
10 Platform for fueling
11 Vertical channels for fuel elements
12 Downcomer pipes
13 High-pressure collector
14 Low-pressure collector
15 Main coolant pipes

Fig. 9.3 Schematic design of the Chernobyl reactor [4, 5]

After the more or less stable power level at 200 MW(th) had been reached, preparations of the experiment continued by activating extra water pumps. This led again to coolant temperature variations and the operators responded by turning off two of the circulating pumps. All these actions led to an extremely unstable reactor state before the experiment began.

Almost all control rods had been removed manually to their upper limit. The automatic control system together with other automated safety features had been disabled. **The reactor coolant temperature was close to its boiling temperature.**

The reactor was already outside of the safe operating envelope established by the designers.

The experiment began by shutting off the steam to the turbine. The turbine generators began to run down. The diesel generators started and picked up loads.

Within the time period of about 1 min until the diesel generators reached full power, the running down turbine generators systems was to support the diesel generators. As the coolant flow rate decreased (the four coolant pumps were also running down; only one coolant pump was to obtain its power supply from the diesel generator and the turbine generator) this lead to increased steam formation (coolant near boiling temperature) in the core. With its positive coolant temperature coefficient and increasing steam formation the reactor theoretically, was now on its way to power runaway.

At this point in time the emergency shut down (SCRAM) bottom was pressed manually. All control rods started immediately to be fully inserted. The control rods moved with a speed of 0.4 m/s into the 7 m high core. The control rods contained a graphite section in their bottom parts followed by absorber sections with boron carbide. During insertion into the upper core neutron-absorbing water was displaced by non-neutron absorbing graphite. This led to an additional increase of the effective neutron multiplication factor k_{eff}. A steep power increase occurred causing the core to overheat. The fuel rods ruptured under the pressure of overheated fuel and fission product gases. The finely dispersed fuel abruptly mixed with the cooling water causing of steam explosion (Sect. 10.2.1). According to theoretical analysis the reactor power jumped to about 30,000 MW(th), ten times the normal operational output. The last reading on the control panel showed 33,000 MW(th). The steam generated caused the destruction of the steam boiler and of core structures and lifted the 2,000 tons top shield together with the refueling machine upwards. Fuel elements and red glowing (not burning) graphite parts were ejected from the core. The reactor building was heavily damaged [8]. A second explosion occurred some seconds later terminating the nuclear reaction and destroying the reactor core and building structures even more, dispersing damaged fuel elements and red glowing graphite parts. There are hypotheses that this second explosion was a second steam explosion or a hydrogen explosion (hydrogen generated from a chemical reaction between the zirconium fuel rod cladding [8]). As bitumen had been used for the construction of the reactor building floor and the turbine hall ejected material ignited fires. The remains of the overheated reactor core were now open to the atmosphere. The fission product gases as well as fission product aerosols and fuel aerosols released were driven by the heat release to an altitude of roughly 2,000 m, in some cases even 10,000 m. Strong winds at these altitude distributed the aerosols over the Ukraine, Belarus, western parts of Russia and Europe. The damaged RBMK1000 (unit 4 of the Chernobyl reactor plant) is shown by Fig. 9.4.

Shortly after the accident firemen arrived to extinguish the fires. Many firemen received very high doses of radiation. The fire was finally extinguished by a combined effort with helicopters dropping 5,000 tons of sand, lead, clay and boron carbide onto the burning reactor. However none of the neutron absorbing boron carbide reached the core [8]. Remotely controlled cranes and bulldozers were used to push back the radioactive material into the reactor. Radioactive debris was shoveled by liquidators wearing heavy protective gears. These workers could only spend a maximum of 40 s working because of the high radioactive doses [9]. There

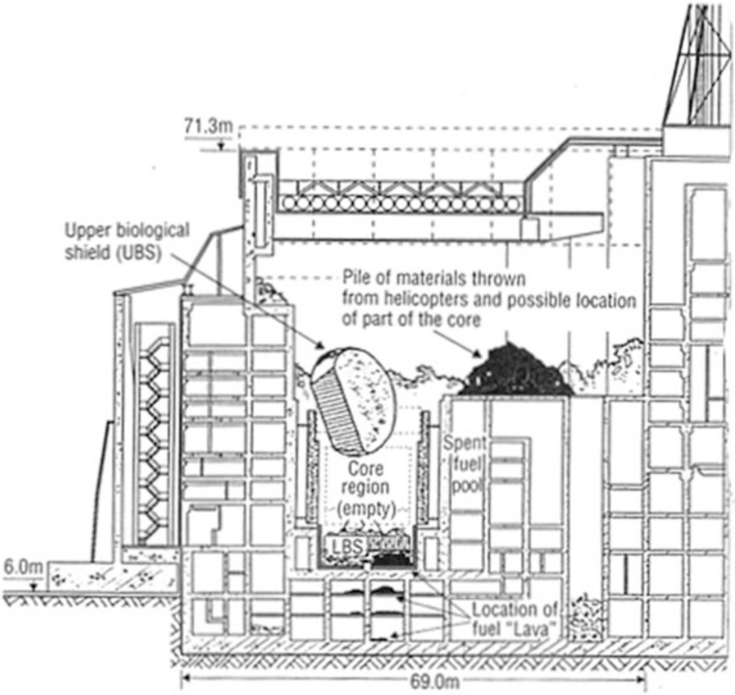


Fig. 9.4 The destroyed Chernobyl reactor after the accident [8]

was fear that the core could melt through the concrete structures. But finally the core mixed with sand, lead etc. and remained within the reactor building.

9.2.1 Radiation Exposure of the Operators, Rescue Personnel, and the Population

Very high, lethal radiation doses and burns in the first phase of the accident were suffered by the firemen, some members of the operating crew, and helicopter pilots dropping, among other things, sand, lead, and boron carbide (31 casualties). Some 1,400 members of the operating crew, scientists, and members of the emergency team (some 200,000 liquidators) were exposed to varying high radiation doses resulting in radiation sickness and radiation injuries.

Different figures are quoted in the literature of up to several thousand additional deaths to be expected in future [6, 7, 9]. According to IAEA data 2011 [6, 7], another 20 persons died afterwards from excessive radiation doses. This number includes roughly five children who died from cancer of the thyroid.

The inhabitants of the nearby cities of Prypjat and Chernobyl were evacuated as late as 30 h after the accident. Their radiation exposure was estimated to be 0.25–

0.5 Sv. On the whole, 135,000 persons were evacuated over the first few days [5]. As a result of varying weather conditions, radioactivity was carried as far as Germany (Chap. 4) and other countries in Western Europe, including Scandinavia.

9.2.2 Chernobyl Accident Management

Hundreds of specialists and approximately 800,000 military men were involved in pushing back the fuel elements into the reactor in "shortest-time activities," piling up sand, lead, boron carbide, and concrete, building a provisional concrete shield, and decontaminating plant compartments. The maximum radiation exposure of these members of emergency teams had been set at 350 mSv [5–9] (see also Chap. 4).

Approximately from 2012 on, the destroyed reactor unit 4 is being enclosed in a new arched sarcophagus [10, 11].

9.2.3 Contaminated Land

As a result of the prevailing weather conditions with precipitation, a number of areas in Ukraine, Belarus and in the western part of Russia were very highly contaminated over the first 10 days. While iodine-131, with a halflife of 8 days, had decayed already after roughly 1 month, cesium-134 (halflife 2 years) for the first 10 years or so and, above all, cesium-137 (halflife roughly 30 years) over approximately 100 years will determine the radiation exposure of the population due to ground-borne exposure and food ingestion [4, 5]. The regions with the highest exposure levels are shown in Figs. 9.5 and 9.6.

Depositions in excess of 40 kBq/m^2 cover large areas in northern Ukraine and southern Belarus. The most highly contaminated zone in Ukraine is the 30-km zone around the RBMK-1000 reactor of Chernobyl with more than 1,500 kBq/m^2.

In the region of Bryansk, Belarus, the highest soil contamination in some villages was measured to be up to 5,000 kBq/m^2. In the Kaluga-Tula-Orel region, contamination of 600 kBq/m^2 was found.

In summary, 3,000 km^2 were contaminated with **more than** 1,500 kBq/m^2 of Cs-137,[1] roughly 7,200 km^2 with 600–1,500 kBq/m^2 of Cs-137, and roughly 103,000 km^2 with 40–200 kBq/m^2 of Cs-137.

Dose exposures for people living in these areas can be estimated from similar dates given in Sect. 9.3.4 for the Fukushima reactor accident.

[1] No upper limit or higher level ranges as in case of Fukushima (Sect. 9.3.4) were published for Chernobyl.

Fig. 9.5 Cs-137 contamination caused by the Chernobyl accident in various regions of Ukraine, Belarus, and Russia [4, 5]

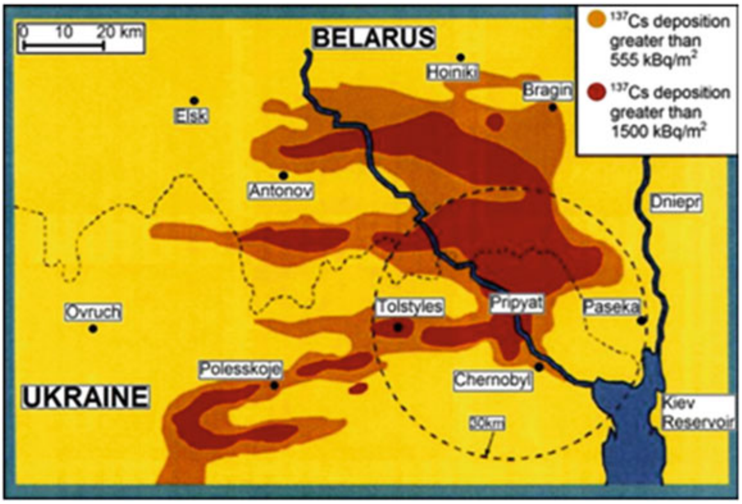


Fig. 9.6 Cs-137 contamination caused by the Chernobyl accident in Ukraine [4, 5]

Lessons Learned The main reasons for the Chernobyl reactor disaster were the wrong design of the RBMK reactors with a positive coefficient of coolant temperature, and also of the control/shutdown systems containing zones of graphite. Moreover, shutting down the automatic protection system and other safety devices by the operators in the course of the test was inadmissible and banned, respectively.

Western light water reactors may be built and operated only with a sufficiently high negative coefficient of coolant temperature.

9.3 The Reactor Accident of Fukushima, Japan

On March 11, 2011, an earthquake of the intensity M = 9 (Richter scale) hit the northeastern coast of Japan east of the city of Sendai (Fig. 9.7). This intensity corresponds to intensity XI on the European MSK/EMS-98 seismic intensity scale [12–21].

Roughly 1 h later, a tsunami wave hit the coast, flooding the Fukushima nuclear power plant up to a water level of 14 m. The earthquake was number four on the list of the severest earthquakes so far registered worldwide; its intensity had not been foreseen by Japanese seismologists when the reactor was designed [15]. Tsunami waves of much greater heights (up to 38 m) had impacted the Japanese coast in the past in the course of earthquakes of lower intensity (Richter scale) (Table 7.14, Sect. 7.4). However, the Fukushima-Daiichi nuclear power plant had been designed only against tsunami waves up to 5.7 m high (Fig. 9.8) [12].

Four nuclear power plants with an aggregate 14 BWRs in the environment of the city of Sendai were hit by the earthquake (with a number of subsequent seismic events) and the tsunami wave on March 11, 2011. These were (Fig. 9.7) the nuclear power plants of Onagawa with three BWRs, Fukushima-Daiichi with six BWRs, Fukushima-Daini with four BWRs, and the Tokai Research Center with one BWR and one research reactor. At that time, only three BWRs were in operation in the Fukushima-Daiichi plant, while the fourth BWR was down (with all fuel elements removed and located in the spent fuel pool), and BWRs 5 and 6 had been shut down for inspection and repair. The eleven BWRs in operation **were duly shut down automatically by the earthquake instrumentation and changed into the residual heat removal mode.**

The seismic waves hitting the Fukushima-Daiichi nuclear power plant from the epicenter caused a horizontal acceleration of 507 cm/s^2 of the most highly loaded reactor of the three units (unit 1). This plant had been designed to 449 cm/s^2. Nevertheless, the BWR was duly shut down. The reactor cooling system and the reactor core were not damaged. In units 2 and 3, horizontal acceleration had not exceeded the design basis levels (Fig. 9.9) [12, 13, 16, 18].

The operating crew immediately started accident management measures in each of the three reactors of the Fukushima plant. First, core cooling was maintained in each of the three reactors by means of the battery power available and a small steam turbine pump system fed by steam from the reactor pressure vessel.

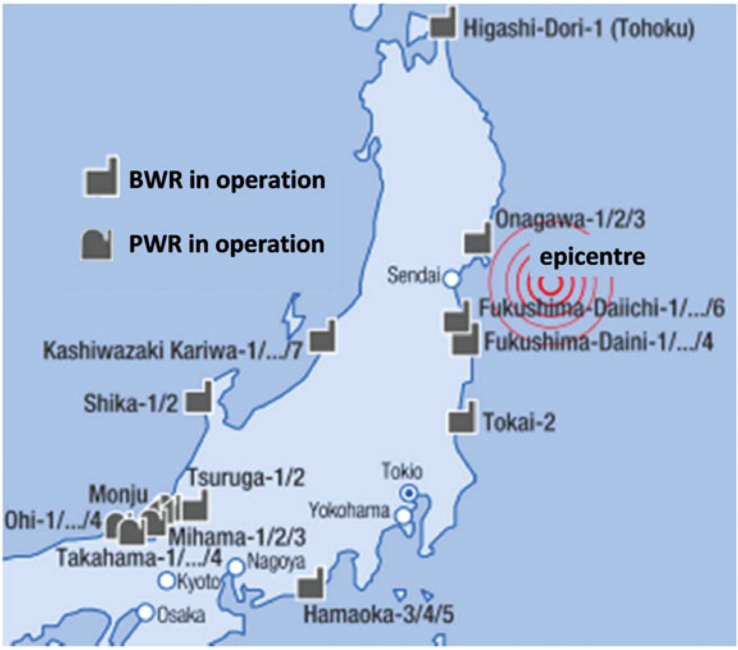


Fig. 9.7 Nuclear power plants operated in Japan (Honshu Island) when the earthquake and tsunami hit the coast [12, 13]

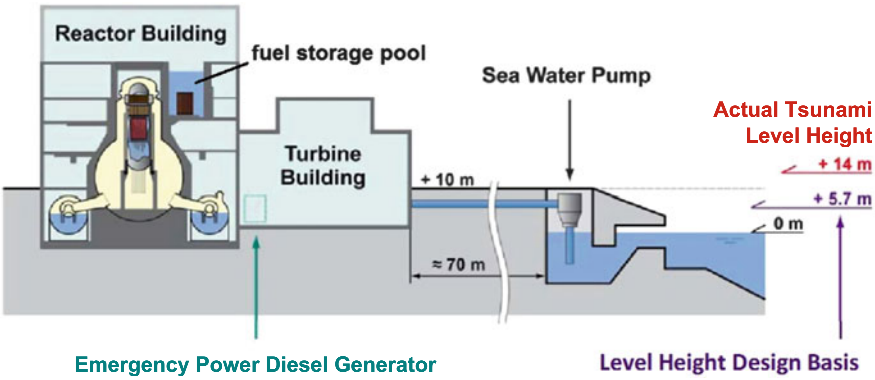


Fig. 9.8 Fukushima-Daiichi reactor plant with countermeasures installed against tsunami waves [12, 13]

However, when the tsunami wave flooded the plants 56 min later, the two diesel generators per reactor of the Fukushima-Daiichi plant units 1–3, installed in the lowest part of the turbine building (Fig. 9.8), were submerged and failed. Also the fuel supply to the diesel generators was partly torn off by the wave. All external grid

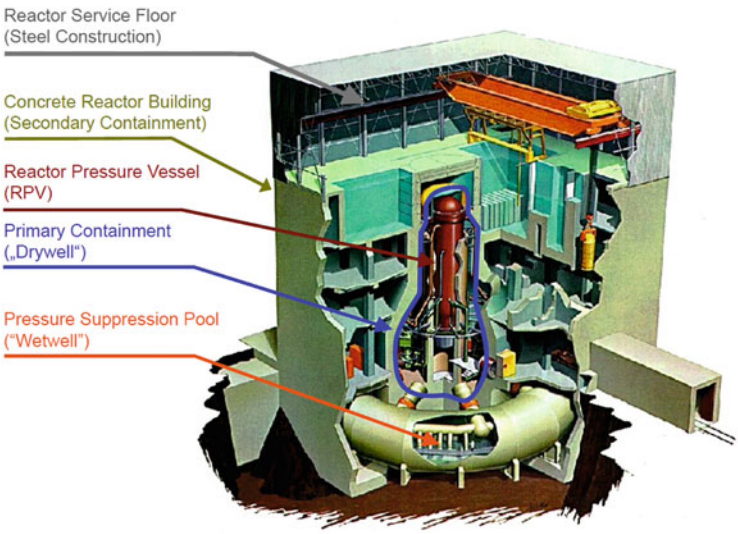


Fig. 9.9 Schematic design of the General Electric BWR-3 boiling water reactor of Fukushima-Daiichi [12, 13]

power supplies to the nuclear power plant had been destroyed already by the earthquake. Also the heat exchangers transferring residual heat to the ocean water outside failed. In addition the direct current batteries which were also located in the basement of the plant were flooded and lost.

In unit 1 due to the loss of all direct current batteries (after flooding) all instrumentation required to control the accident became unavailable. The operator crew had to work in the dark. The high pressure coolant injection system did not work, because of loss of power from the submerged diesel power generators (emergency power supply). The isolation condenser system (steam driven pumps) worked only partially. The primary coolant system with the reactor pressure vessel was not depressurized, because of lack of electrical power or pressurized nitrogen and lack of knowledge about the actual state in the various vessels due to the lost instrumentation. Therefore, low pressure emergency pumps could not feed water into the primary system for core cooling. The primary coolant system heated up and soon exceeded its design pressure, the core became uncovered by coolant and the fuel rods started to melt down. Hydrogen was produced because the fuel rod claddings (Zirconium) exceeded temperatures of 1,200 °C and reacted with steam.

$$Zr + 2\,H_2O \rightarrow ZrO_2 + 2\,H_2.$$

The pressure in the reactor pressure vessel was soon relieved into the primary containment because core melt penetrated the lower bottom wall by small holes or by a break of a low elevation pipe of the pressure vessel or by opening of a safety/relief valve. The radioactive noble gases and the volatile fission products such as

Cs-134, Cs-137, Sr-90 etc. were released into the pressure vessel and into the primary containment. The water in the primary containment with pressure suppression chamber heated up and its design pressure was soon exceeded (Fig. 9.9). Leakage paths within the primary containment vessel led to hydrogen release into the upper part of the reactor building (Fig. 9.10). About 1 day after the earthquake and the impact of the tsunami wave on unit 1 a hydrogen detonation occurred in the upper part of the reactor building. It destroyed the upper structures of the reactor building. Four technicians were injured [20, 21].

The records did not show any deliberate attempt by the operation crew to depressurize the reactor pressure vessel during the accident course. This would have been necessary to add water by emergency pumps. Only about 2 h after the hydrogen detonation, when the primary coolant system had depressurized itself, the operators could begin feeding in fresh water using fire pumps [21]. However, the longer term water level in the reactor pressure vessel did not recover to more than midplane, regardless of the make-up water quantity being added. This indicates a low elevation leak in the pressure boundary of the reactor pressure vessel.

The accident developed in an almost similar pattern in units 2 and 3, though with a larger shift in time. The reactor core isolation cooling system worked longer (for 70 h in unit 2 and 20 h in unit 3). When this emergency cooling system failed in units 2 and 3 the operators tried to depressurize the reactor pressure vessel in order to inject water using the fire extinguisher lines. Problems occurred, however, due to the lack of electricity for the solenoid valves and lack of pressurized nitrogen to open the safety/relief valves. Therefore, water could not be injected for about 6.5 h in unit 2 and for about 7 h in unit 3. The core fuel became uncovered in both units. The fuel heated up, was significantly damaged, hydrogen was produced and volatile fission products and radioactive noble gases were released into the primary containment. A longer term water level in the reactor pressure vessel could not be restored to higher than about midplane in both units 2 and 3, indicating also a low elevation leak in the pressure boundary of the reactor pressure vessel. The primary containment pressure increased. Hydrogen was released probably through leakage paths as the containment vent lines could not be opened. This was due to not high enough pressure to break a rupture disk. As a consequence a hydrogen detonation occurred also in unit 3. In unit 2 no hydrogen detonation happened [21].

Also in unit 4 the total emergency electricity supply (diesel generators and batteries) was lost. This lead to an increase of the coolant water temperature in the fuel storage pool of unit 4. At 6 AM on March 15 a hydrogen explosion also occurred in this reactor building (unit 4), severely damaging its upper structures. At first it was thought to be due to hydrogen production from fuel heat up and coolant uncovery in the spent fuel pool. Later, photographs indicated that there was no overheat damage of that fuel in the spent fuel pool. The source of hydrogen was traced to be a backflow through the standby gas treating system shared as common piping with unit 3 [21].

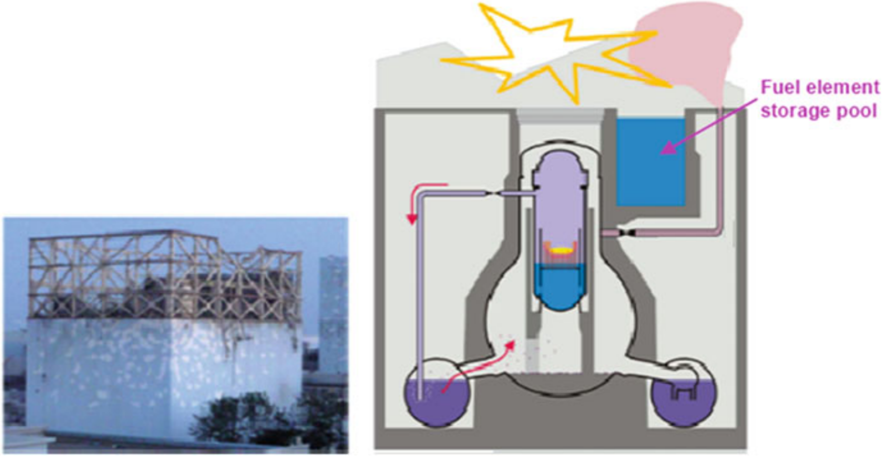


Fig. 9.10 Hydrogen explosions within the reactor auxiliary systems building destroyed the upper steel structure and the roof [12, 13]

9.3.1 Spent Fuel Pools of the Fukushima Daiichi Units 1–6

9.3.1.1 Unit 1

When the hydrogen detonation occurred and damaged the upper building structure, material might have been falling into the spent fuel pool. There is, however, no evidence that the fuel was damaged. A concrete pumping truck was used to provide makeup water inventory. An alternative cooling water system was put in service soon afterwards. The cooling water temperature has been maintained <35 °C [21].

9.3.1.2 Unit 2

Using existing piping water addition to the unit 2 spent fuel pool was possible. No fuel was damaged. A dedicated system using a heat exchanger was put in service afterwards. The cooling water temperature has been maintained <35 °C [21].

9.3.1.3 Unit 3

After the upper building structure had been destroyed by the hydrogen detonation water cannons were used for spraying water and helicopters dropped water into the spent fuel pool of unit 3. Then concrete pumps provided water addition to the spent fuel pool. The use of existing piping to restore water cooling started soon afterwards. Photographs showed that parts of the building structures had fallen into the pool. It is likely that no damage has occurred to the spent fuel. The cooling water temperature had been maintained <35 °C [21].

9.3.1.4 Unit 4

After the upper building structure had been destroyed by the hydrogen detonation, initially, water was sprayed by water cannons and concrete pumps. The structures supporting the spent fuel pool of unit 4 were improved by steel support pillars to provide protection against damage that might result from additional seismic events. Photographs showed that the fuel racks of the spent fuel pool of unit 4 were intact. A cooling system for the spent fuel pool was put in service. The coolant temperature of the spent fuel pool had been maintained <40 °C [21].

9.3.1.5 Units 5 and 6

No damage occurred to the fuel in the spent fuel storage pools 5 and 6. One Diesel generator of the units 5 and 6 could be restored soon enough such that emergency electric power was available for the cooling of the spent fuel [21].

9.3.2 Measurement of the Radioactivity Released

Large parts of the radioactivity released were initially carried out to the sea by the prevailing winds. Measurements of the radioactivity released over land (radioactive noble gases, radioactive I-131 (halflife 8 days) and radioactive aerosols, such as Cs-134 (halflife 2 years) and Cs-137 (halflife 30 years)), were carried out by specially equipped aircraft of the American National Nuclear Security Agency (NNSA). These measurements (Fig. 9.11) showed a particularly pronounced distribution of radioactivity towards the northwest of Fukushima. The measurements were evaluated in order to determine the radioactive exposure, which must be known for decisions about evacuation of the public. The Japanese government then evacuated the population (roughly 200,000 persons) in the vicinity of the nuclear power plants. The initial evacuation zone was soon expanded to a radius of 20 km. Afterwards, also some places situated beyond the zone of 20 km were evacuated because the annual dose to the population there had been estimated to run up too high [18, 19].

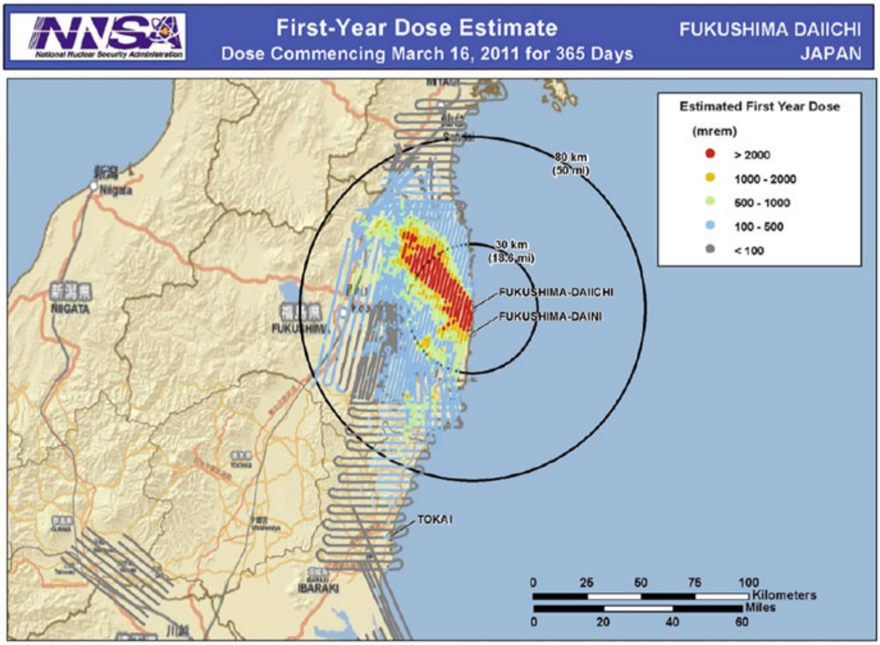


Fig. 9.11 Measured radioactivity and calculated dose levels from radioactive exposure within the first year after the accident of March 11, 2011 [16–19, 21]

9.3.3 Damage to Health Caused by Ionizing Radiation

Three months after the accident, the IAEA in Vienna found that the population had not suffered any measurable damage to health as a result of ionizing radiation [16].

The lifetime baseline risk (probability of having a specific cancer over the lifetime of 89 years of a person) was reported by the World Health Organization (WHO) [19] in a detailed analysis for children and adults.

Four members of the operating crew were killed by the earthquake and the following tsunami wave. Some 20 staff members were injured by the hydrogen explosions. There were in total 23,172 emergency and mitigation workers working at the Fukushima Daiichi reactor plants. According to a report of the World Health Organization (WHO) [19] most of them received <10 mSv total effective radiation dose. 75 workers received up to <200 mSv and 12 workers received up to 700 mSv total effective radiation dose (two of them had sustained β^--radiation exposures of the legs from contaminated water). The level laid down by the Japanese government was a maximum radiation exposure of rescue workers of 250 mSv [16–19, 21] (see also Sect. 4.4.3).

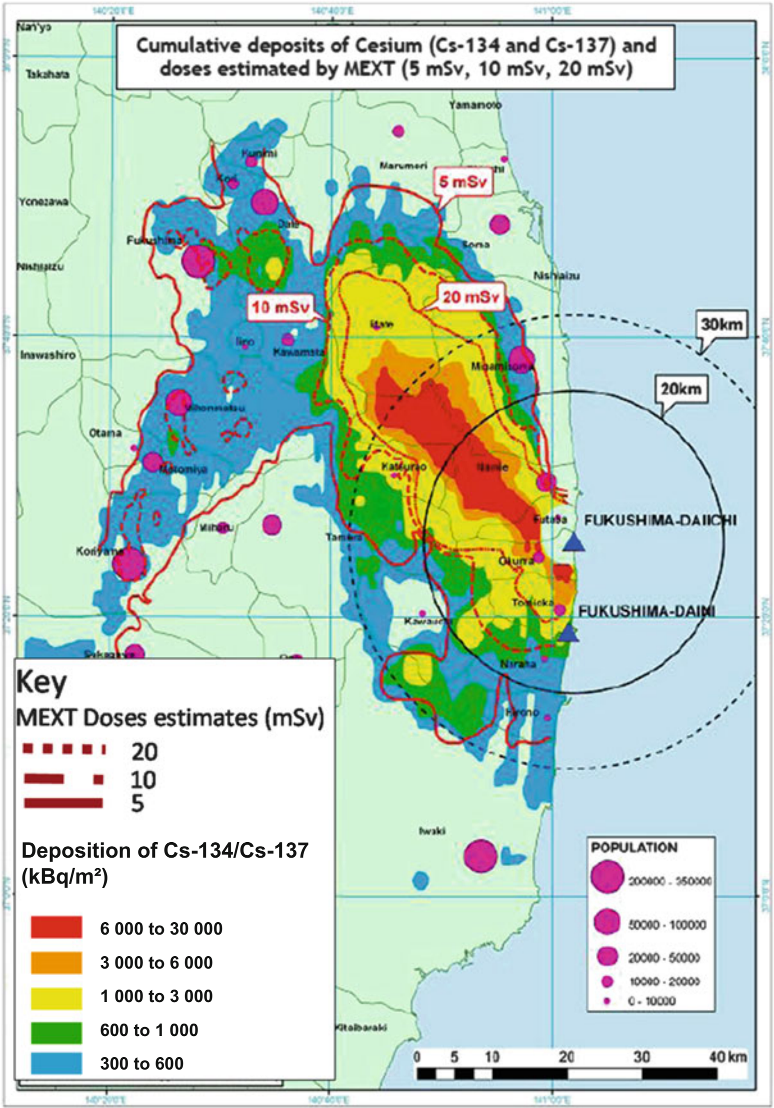


Fig. 9.12 Areas of Cs-134 and Cs-137 deposits in kBq/m^2 as well as estimates for radiation exposure of the Japanese public in certain locations during the first year after the Fukushima-Daiichi accident [18, 21]

9.3.4 Contamination by Cs-134 and Cs-137

While iodine-131, with a halflife of 8 days, had decayed within a month, depositions of Cs-134 stay on the ground for about 10 years, and depositions of Cs-137 remain for roughly 100 years. Japanese, French, and American measurements of ground depositions of cesium are shown in Fig. 9.12.

The results indicate the most highly exposed zone due to Cs-134 and Cs-137 with 6×10^6 to 30×10^6 Bq/m^2 to be in the northwestern direction from the Fukushima-Daiichi plant. Other zones show lower soil contamination levels due to cesium. Evaluations indicated regions in which persons, if they lived there and consumed only food available locally, would suffer a radiation exposure of 5 mSv/year and 10 mSv/year or 20 mSv/year, respectively, within the first year after the accident (This must be compared with the world wide effective annual radiation dose 2.4 mSv/year) [19] and the 8–100 times higher annual natural radiation exposure in Kerala, India or Brazil (Sect. 4.3). In the regions more highly exposed to radioactive cesium, 3,100 persons, if they were to return there, would suffer 50 mSv/year, and 2,200 persons would not be allowed to enter the "no-entry" zone. They would be exposed there to 100–500 mSv/year [17].

The Fukushima accident was classified in top category 7 of the international event scale of reactor accidents drafted by IAEA.

9.3.5 Lessons Learned

Despite the earthquake of Richter scale 9, the reactor units of Fukushima-Daiichi were shut down automatically as planned. The emergency power diesel generators supplied the internal grid as planned for almost 1 h until the tsunami hit.

The disaster occurred because the reactor facility had been designed only against a tsunami wave of 5.7 m height. The tsunami wave of 14 m height caused the emergency power diesel generators and direct current batteries to fail. Unfortunately, they had been installed at the lowest point (the basement of the turbine hall). The compartments of this turbine building could not be shut watertight.

Due to the failure of the diesel generators and the loss of the direct current batteries the reactor pressure vessel could not be depressurized (safety/relief valves could not be opened). The high pressure water injection system failed. The isolation condenser system worked only partially.

The efforts of the operators to start emergency core cooling by means of low pressure fire pumps failed. Water could not be injected because of the high pressure in the reactor. This caused the water level in the reactor pressure vessel to drop, the temperature of the fuel claddings to rise, hydrogen to be produced, the fuel elements to melt down, and fission products to be released into the pressure suppression chamber. The absence of hydrogen recombiners in the inner containment, and the non-availability of means for the depressurization of the hydrogen mixed with steam and fission products to be passed through aerosol filters in the stack of the plant, led after leaks out of the inner containment to hydrogen explosions and destruction of the relatively lightweight roof structure. The fuel element storage pool was uncovered. Radioactive iodine and, above all, radioactive cesium were released into the atmosphere.

9.3.5.1 Comparison with the Safety Design of Other Nuclear Power Reactors

The question whether the Fukushima-Daiichi accident scenario is also representative for other nuclear power plants in the world can be answered as follows:

Tsunami waves must only be expected for nuclear power reactors built near the ocean. LWRs in Europe and the USA are designed against floods occurring once in about 10,000 years, including waves, hurricanes, failure of dams, etc. (Chap. 7).

Most of the presently operating nuclear power reactors in Europe and the USA have similar safety design characteristics as pressurized water reactors and the boiling water reactors described in Chap. 3. These have a second emergency diesel power grid system protected against airplane crash and other external events, which ensures both cooling of the reactor core by way of the steam generators and cooling of the fuel element pools. The emergency power building, like the regular emergency power diesel buildings, **is protected against flooding**. The air intake openings of the diesel generators are located in the upper region of the building [20]. German pressurized and boiling water reactors—as an example—are equipped with hydrogen recombiners (backfitting) which recombine the hydrogen produced in accident situations within the inner containment. Boiling water reactors have inner containments which are inertized by nitrogen. The containments of pressurized water reactors in Germany—as an example—will resist to large scale hydrogen detonations (Chap. 10).

Boiling water reactors have the appropriate emergency buildings with the same functions as pressurized water reactors [20]. First of all, steam-driven turbopumps are available for emergency core cooling. Then pressure relief is initiated, and the inventory of the feed water tank—as an example in Germany—is passively fed into the reactor pressure vessel. The reactor core can be cooled by means of mobile pumps kept in the emergency building. There are several possibilities of feeding the reactor core with water by mobile pumps up to and including pumps of the firefighting system. The feed water reservoirs available include the demineralized water tanks (tanks for water of very high purity), the drinking water system, internal wells, and river water (severe accident management measures (Chap. 10)).

9.3.6 Recommendations Drawn from the Fukushima Accident

9.3.6.1 Recommendations of the American Nuclear Society Special Committee on Fukushima

A committee of the American Nuclear Society with safety experts from the USA and Japan made the following recommendations after thorough analysis of the Fukushima accidents [21].

- Flooding protection of diesel generators and direct current batteries is essential. Independent direct current connection should be provided for critical instrumentation, critical valve operation and control functions
- Ensure adequate dike heights against flooding of the emergency diesel generators and the direct current batteries. Provide diversity for both alternate and direct emergency power supply
- Provide robustness of the reactor core isolation cooling system (steam driven pumps and generators) in Boiling Water Reactors
- Improve the reliability to depressurize the reactor pressure vessel and maintain it depressurized during station black out (loss of all electrical power)
- Improve the reliability to vent the primary containment in Boiling Water Reactors
- Improve the instrumentation in the reactor pressure vessel to provide the operator with more knowledge about the course of a core accident.
- Provide the inner containment of Boiling Water Reactors with hydrogen recombiners
- The possibility of an earthquake damaging the wall of the liner of the spent fuel pool causing cooling water to be lost should be considered. A hardened strong pipe—as already realized in US reactor plants—should be installed which allows water to be fed to the spent fuel pool from the outside.

9.3.6.2 Additional Recommendations Drawn from the Fukushima Accident

The emergency power supplies (diesel generators, gas turbines, fuel cells direct current batteries) should be arranged in a building protected against tsunamis, flooding, earthquakes, hurricanes etc. An emergency operation room with the essential instrumentation power supply and the ability to operate the plant in case it cannot be operated from the main operator room should be available.

9.4 Comparison of Severe Reactor Accident on the International Nuclear Event Scale

The International Atomic Energy Agency (IAEA) introduced in 1990 the International Nuclear and Radiological Event Scale (INES) as a measure to compare severe nuclear accidents and their radiological impact on international scale. It represents seven increasing levels. Each level about a factor more severe than the previous level [22]. Figure 9.13 shows the INES scale in form of a pyramid.

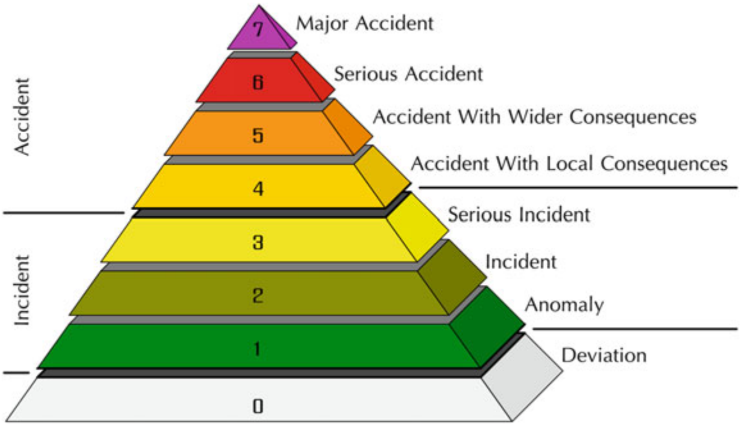


Fig. 9.13 International nuclear event scale [22]

Level 0: Deviation

– Classifies: Deviations of no safety significance, e.g. leakage from a primary coolant circuit

Level 1: Anomaly

– Classifies: impact on the defense in-depth, e.g. damaging of a fuel element during unloading process

Level 2: Incident

– Classifies: impact on radiological barriers, on people or environment, e.g. radiation levels in an operating area of more than 50 mSv.

Level 3: Serious incident

– Classifies impact on radiological barriers, on people or environment, e.g. radiation levels in an operating area of more than 1 Sv/h.

Level 4: Accident with local consequences

– Classifies: impact on radiological barriers, on people or environment, e.g. SL-1 accident (USA). Experimental reaction SL-1 reached prompt criticality killing three operators.

Level 5: Accident with wider consequences

– Classified: impact on radiological barriers, on people or environment, e.g. Windscale accident in the United Kingdom in 1957, Three Mile Island Accident near Harrisburg (USA) in 1979.

Table 9.1 INES classification of the most severe nuclear reactor accidents

Reactor	Windscale	Three Mile Island	Chernobyl	Fukushima Daiichi
INES-classification	Level 5	Level 5	Level 7	Level 7

Level 6: Serious accident

– Classified: impact on people and environment, significant release of radioactivity to require planned countermeasures, e.g. Kyshtym disaster at Mayak, Russia. A failed cooling system at a military nuclear waste reprocessing facility caused a steam explosion which led to release of 70–80 tons of highly radioactive material into the environment.

Level 7: Major accident

– Classified: impact on people and environment

Major release of radioactive material with wide spread health and environmental effects requiring planned and extended countermeasures.

Examples are:

– The Chernobyl disaster in 1986, Ukraine,
– The Fukuschima Daiichi nuclear disaster in 2011, Japan

Following this classifications of the Instrumental Nuclear and Radiological Event Scale (INES) the severe accidents of Windscale, Three Mile Island, Chenobyl and Fukushima are listed in Table 9.1.

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