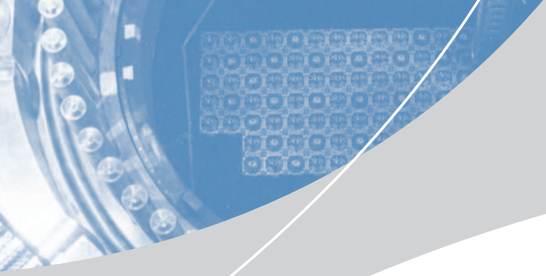

The severe Tohoku Seaquake in Japan and its impact on the Fukushima Daiichi nuclear power plant

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Bernhard Kuczera, Karlsruhe/Germany, and Ludger Mohrbach, Essen/Germany

On Friday, March 11, 2011, Japan experienced a natural disaster of unprecedented dimensions. At 14.46 p.m. local time (6.46 a.m. CET), a gigantic earthquake with its epicentre approximately 160 km East of the city of Sendai in the Pacific Ocean also shook the coastal regions nearby.

The seismic event was triggered by abrupt tectonic plate shifts some 20 to 30 km below sea level. The seaquake had a magnitude of 9.0. This unexpectedly high energy release caused a tsunami wave of a maximum height of 23 m, which flooded the coastal region of northeast Honshu approximately one hour later, causing a large number (in excess of 25,000) of human casualties and extreme devastation of buildings, other infrastructure and the environment.

Four nuclear power plants are located in the area directly affected by the disaster: Onagawa, Fukushima Daiichi, Fukushima Daini, and Tokai. The site of Fukushima Daiichi was hit most intensely. The effects of the tsunami on the Fukushima Daiichi plant are outlined in the following, i.e. tectonic shifts, impact of the tsunami, and countermeasures taken by the operator, Tokyo Electric Power Company (Tepco), on the basis of information available at the editorial deadline (mid May 2011).

Introductory remarks on the natural disaster

The quake on Friday, 11 March 2011, with a magnitude of 9.0 was a so-called inter-plate rupture, much stronger than the frequent intra-plate earthquakes with typical magnitudes up to around 7 Japan is more or less used to (*Figure 1*).

The seismic event was triggered by an abrupt tectonic plate shift some 20 to 30 km below sea level. The pacific plate is subducing the Eurasian and the Philippine plates in that area with a velocity of 83 mm per year. The plate displacement reached up to 17 to 25 m, the rupture area stretched over 500 km in length and about 100 km in width. Since then, hundreds of secondary quakes with magnitudes up to more than seven have marked that area.

The displaced water produced a tsunami, which reached a calculated and GPS-measured maximum height of 23 m, travelling in hours across the whole Pacific ocean.

Within one hour after the quake, the tsunami reached the North-East Honshu coast and flooded the adjacent regions. Seaquake and tsunami caused a large number of casualties and severe devastation on the coast. By the end of March 2011, media reported that about 13,000 people had lost their lives and more than

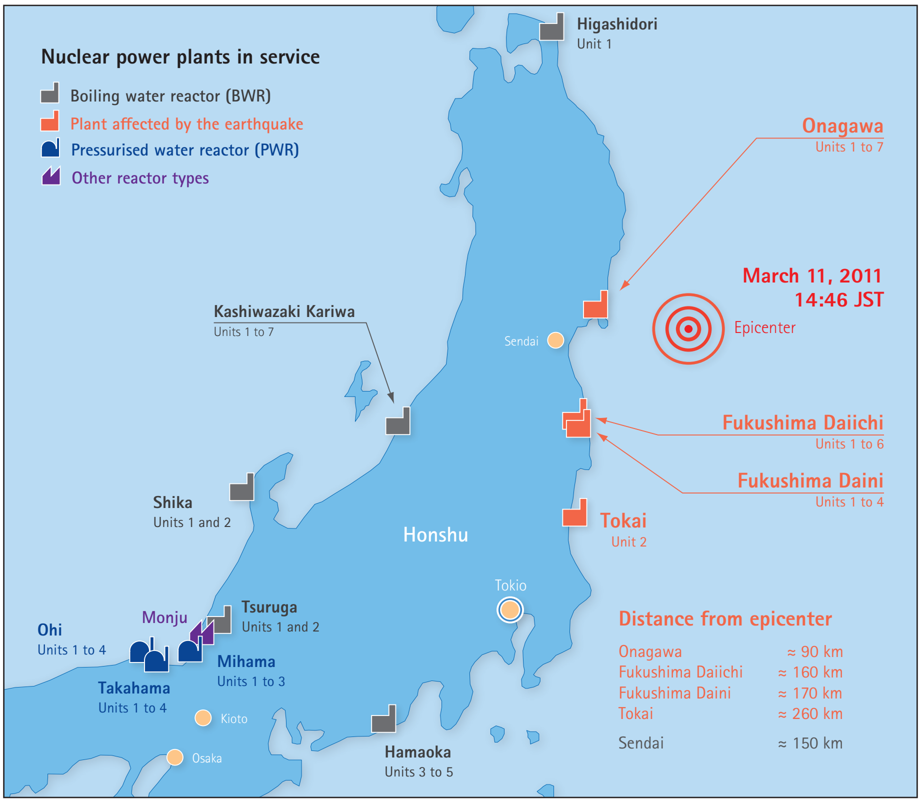

Fig. 1. The epicentre of the seaquake off the Japanese Pacific coast.

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15,000 were missing. 320,000 people had to stay in emergency accommodation. According to current Japanese Government estimations, the damage to property will amount to at least 220 billion €.

Four nuclear power plant sites are located in the direct vicinity affected by this nature disaster: *Onagawa 1* to *3, Fukushima Daiichi 1* to *6, Fukushima Daini 1* to *4* and *Tokai 2*. The *Fukushima Daiichi* site was most badly hit. In the following it will be outlined how the site was affected by the quake and the tsunami and which measures were taken by the operator, *Tokyo Electric Power Company (Tepco),* to protect the environment and to limit damage[1].

1 Short description of the Fukushima Daiichi power plant

The *Fukushima Daiichi* plant is located about 60 km South of Sendai, the capital of the Japanese prefecture of Miyagi, and about 250 km North of the Japanese capital of Tokyo.

Figure 2 shows a photo of the plant taken before 11 March 2011. The plant comprises six boiling water reactors (BWR) with their turbine and auxiliary buildings located on a low plateau directly on the Pacific coast line. Together, the six units had a total output of 4,696 MWe_{gross} and 4,547 MWe_{net} [2], thus forming together with the adjacent *Fukushima Daiini* site (4 BWRs with a total of 4,400 MW_{gross} and 4,268 MWe_{net}, located about 11 km South of the *Fukushima Daichii* site) the largest nuclear power plant complex in the world.

Figure 3 shows unit 1 of *Fukushima Daiichi* with its main safety- and protection devices (e.g. the Mark-I containment of units 1 to 5) as an example for the typical BWR design at the *Fukushima Daiichi* site which corresponds to the BWR-3-design by *General Electric (GE)*. Units 2 to 5 are of the *GE* type BWR-4 and unit 6 of the *GE* type BWR-5. The safety concept for retaining fission products is also depicted: it comprises the barriers – arranged successively – fuel, cladding tubes, (both not shown in the figure), reactor pressure vessel, primary containment (drywell) including condensation chamber (wetwell) and the external reactor building made of reinforced concrete or steel structures (confinement or secondary containment). The pool for storing spent fuel is located in the upper part of the reactor building, however, inside the secondary containment. In this pool, the spent fuel elements (FE) have to be stored intermediately and cooled to remove the decay heat[3] that is still being produced. The storage basins for the reactor vessel head, moisture separator and steam dryer are also located in that area. The design basis of the structures for dynamic loads corresponded to an earthquake of magnitude 8.2.

Fig. 2. *Aerial photo of the Fukushima Daiichi nuclear power plant before March 11, 2011.*

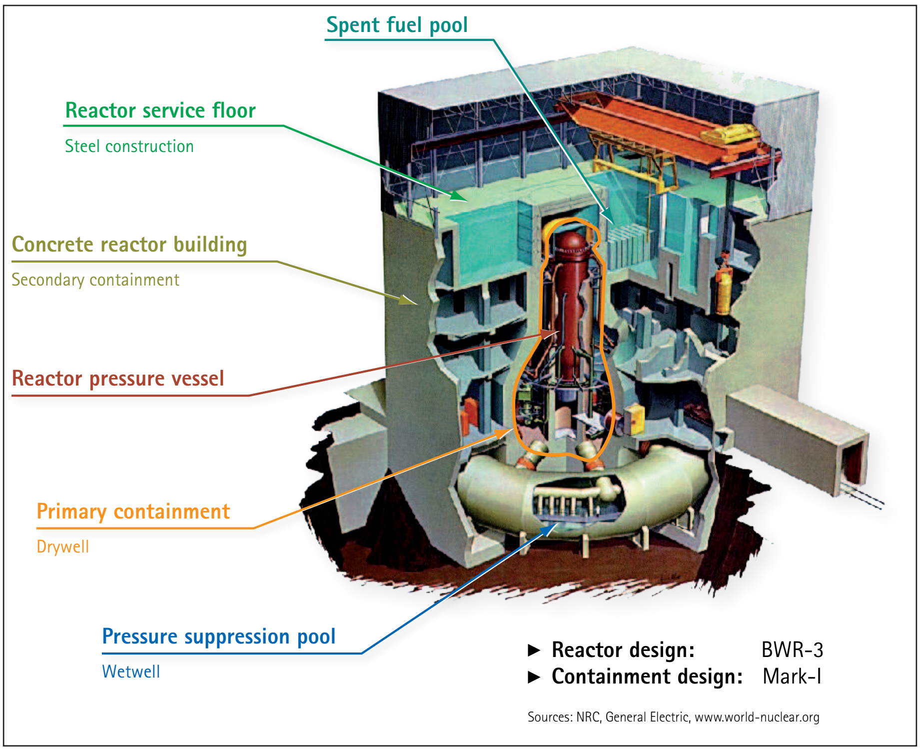

Fig. 3. *BWR design of the Fukushima Daiichi unit 1; BWR-3 with Mark-I containment. The containment is characterised by the torus-shaped pressure relief system in the lower part of the reactor building.*

The operating state of the individual plant units prior to the quake is listed in *Table 1*.

2 The natural disaster in the region Fukushima Daiichi

2.1 The earthquake

On 11 March 2011, seismographs registered at 14:46 h severe ground vibrations at the above mentioned nuclear power plants, triggering automatic shutdown (scram) of all operating 11 units at the 4 sites, in *Fukushima Daiichi* of the units 1, 2 and 3 that had been in operation. At the same time, the

1 Until editorial deadline, May 2011

2 By the end of 2010, a total of 55 nuclear power plants were in operation in Japan with a total capacity of 49,400 MWe (gross). They contributed with 29 % to the total electricity supply of the country.

3 The decay heat of a reactor amounts to some 5 % immediately after reactor shutdown, to 1 % after about one hour, to 0.44 % after one day, to 0.23 % after about one week, to 0.13 % after one month and to 0.007 % after approximately three months of the output that was generated at the time of unit shutdown.

Parameter	Nuclear power plant site Fukushima Daiichi					
	Uni 1	Unit 2	Uni 3	Unit 4	Unit 5	Unit 6
Start of commercial operation	1971	1974	1976	1978	1978	1979
Reactor design	BWR-3	BWR-4	BWR-4	BWR-4	BWR-4	BWR-5
Containment design	Mark-I	Mark-I	Mark-I	Mark-I	Mark-I	Mark-II
Thermal power in MW	1380	2381	2381	2381	2381	3293
Electric power ¹) in MW	460	784	784	784	784	1100
Electric power ²) in MW	439	760	760	760	760	1067
Reactor pressure vessel						
❑ Maximum pressure in MPa	8.24	8.24	8.24	8.24	8.62	8.62
❑ Maximum temperature in °C	300	300	300	300	302	302
Containment						
❑ Maximum pressure in MPa	0.43	0.38	0.38	0.38	0.38	0.28
❑ Maximum temperature in °C	140	140	140	140	138	171 ³)
Emergency diesel generators	2	2	2	2	2	3
❑ Water-cooled	2	1	2	1	2	2
❑ Air-cooled	0	1	0	1	0	1
External electric supply	4 x 275 kV				2 x 500 kV	
Status before earthquake ⁴)	in service	in service	in service	outage	outage	outage

¹) gross ²) net ³) wetwell: 105 °C ⁴) on March 11, 2011

Tab. 1. The operating status of the power plant unit at the Fukushima Daiichi site immediately before the earthquake and technical key data.

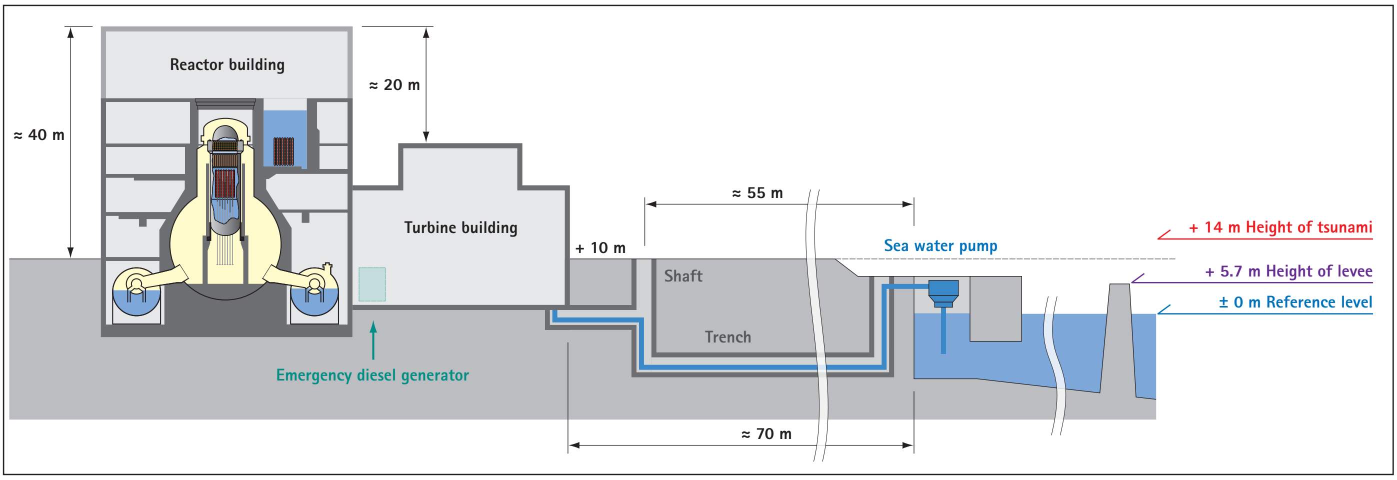

Fig. 4. The height of the tsunami wave relative to the level of the nuclear power plant's facilities.

regional public power supply broke down due to collapsed high-voltage lines. The emergency diesel sets took over power supply for the cooling systems that are required for removing decay heat from the operating reactors and the spent fuel pools of all six units. At the same time, the primary containment was isolated by shutting all penetrating pipes (including main steam and feedwater) not needed for removing residual heat .

The seismic shocks produced a horizontal ground acceleration at the power plant site in East-West direction of up to 550 cm/s^2, up to 25 % higher than the design basis value. No major damage was reported to be caused by the seismic shocks. The units were all in a stable state in that phase.

2.2 The tsunami wave

About one hour later, at 15:41 h, the *Fukushima* coast was hit by the tsunami wave with a height of about 14 metres at the Daiichi site. The seawall with a height of 5.7 metres (see Figure 4) might have absorbed some of the wave's impact, but was easily inundated. However, the site ground level of 10 m submerged, causing severe damage to all seaward installations and flooding the turbine halls after breaking their doors.

All emergency diesel generators, located on the turbine hall floor below ground level, except one air-cooled extra set in unit 6, were knocked out by the water ingress, leaving the units 1 to 4 without AC power supply (the remaining diesel was afterwards able to supply AC electricity for units 5 and 6, see *Table 1*).

Thus units 1 to 4 saw a total station blackout (see also *Figure 5*).

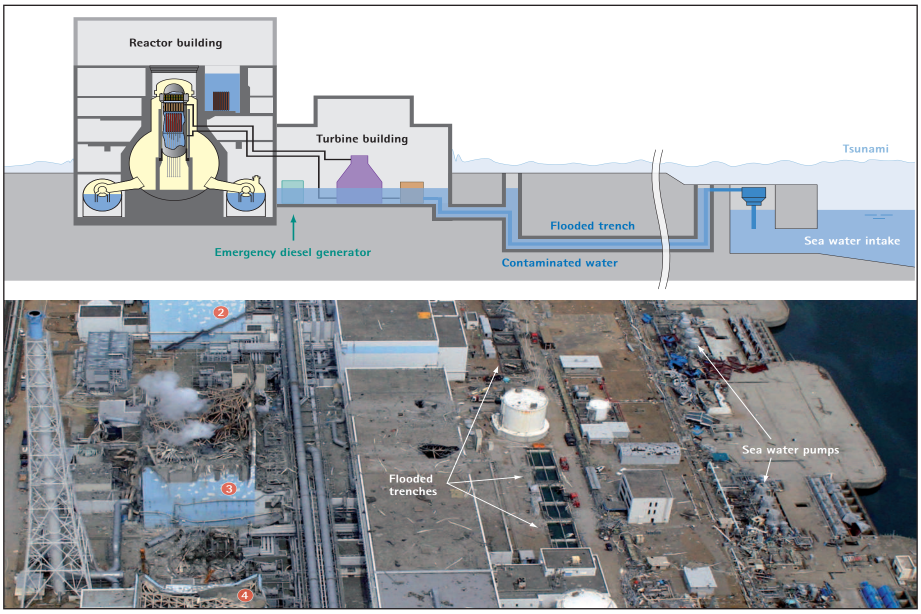

Fig. 5. Flooding of the turbine hall basement.

2.3 Accident development in the Fukushima Daiichi power plant and accident management to limit accident consequences

When the diesel generators failed, only the passive emergency core cooling systems, the so-called isolation condenser in unit 1 and steam-turbine driven high-pressure injection systems in units 2 and 3 were left to provide residual decay heat removal. These systems worked as long as the batteries had enough capacities to provide auxiliary power (some hours), and as long as the temperature of the heat sink in the wetwell (the torus) had not reached saturation conditions.

The accident scenario that developed in the following has been basically known from risk studies. It is shown in sequential pictures and according to [1] in a self-explanatory way in *Figures 6a* to *6f*.

For unit 1, this scenario resulted on Saturday, March 12, 2011, at 15:36 h in an explosion of hydrogen formed from the reaction of the fuel cladding material zirconium with water at high temperatures, as shown in *Figure 6f*. It has not been settled yet how hydrogen could escape from the reactor core to the upper parts of the reactor building, instead of being vented through the exhaust stack.

The explosion destroyed the steel wall structures of the upper part of the reactor building, above the reactor service floor, where also the spent fuel pool is situated ("secondary containment"). Consequently, gaseous and volatile fission products escaped into the atmosphere.

At this stage, the core must have been uncovered, fuel rods damaged, relocating the fuel pellets downwards, where they are suspected to have reached fuel melting temperatures.

In units 2 and 3, the sequence of events was similar and resulted in a hydrogen explosion on the service floor of unit 3 on March 13, 2011, at 11:02 h and another explosion sound was heard from within unit 2 on March 15, 2011, at 6:10 h. Destruction of the secondary containment in unit 3 was comparable, unit 2 escaped an explosion probably because of a leak in the outer building wall.

It has also not been known yet which systems had been available and which systems had failed at what point in time and how and for what reason the hydrogen explosion had developed. In all three units, operators had opened primary containment venting valves manually to depressurise the primary containments at around 8 bars (design pressure 4 to 5 bars) to reach "cold shutdown", after declaring emergency conditions to the regulatory bodies. On March 11, 2011, six hours after the tsunami, the government took first preventive measures to protect the public from elevated radiation exposure at a 2-km radius around the *Fukushima* site. On March 12, 2011, about four hours after the first hydrogen explosion in unit 1, the measures were extended: the area around *Fukushima Daiichi* was evacuated gradually at a larger radius. So far, more than 200,000 people have been asked to leave their homes.

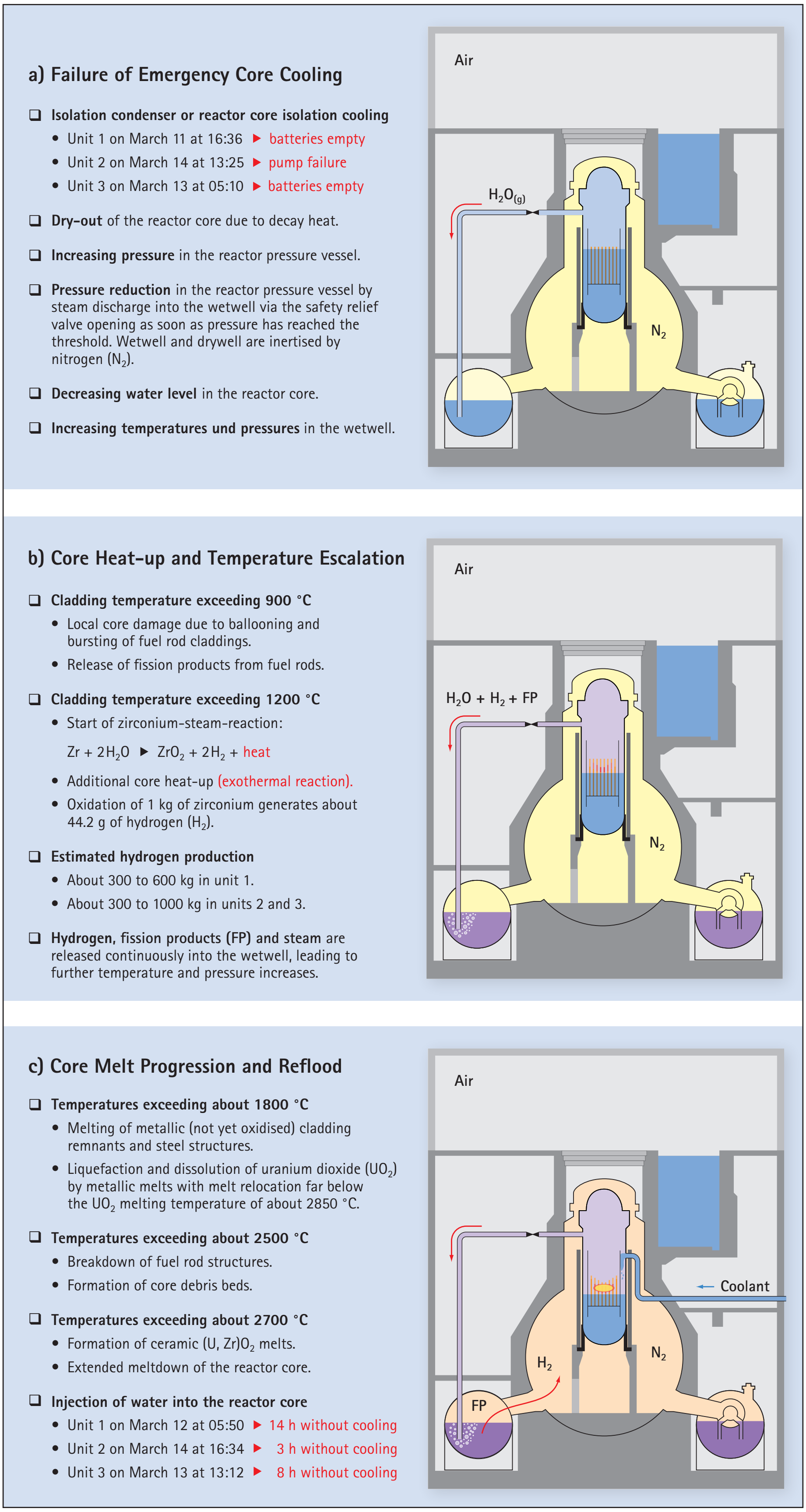

Fig. 6 a–c. Development of the accident in the Fukushima Daiichi unit 1 [1].

The development in the units 4, 5 and 6 of the *Fukushima* plant was different. In November 2010, all fuel assemblies had been withdrawn from the reactor of unit 4 for reasons of inspection. The fuel assemblies were stored in the spent fuel element storage pool. Correspondingly, the decay heat was relatively high in the spent fuel pool of unit 4 with a total of 1,331 fuel elements

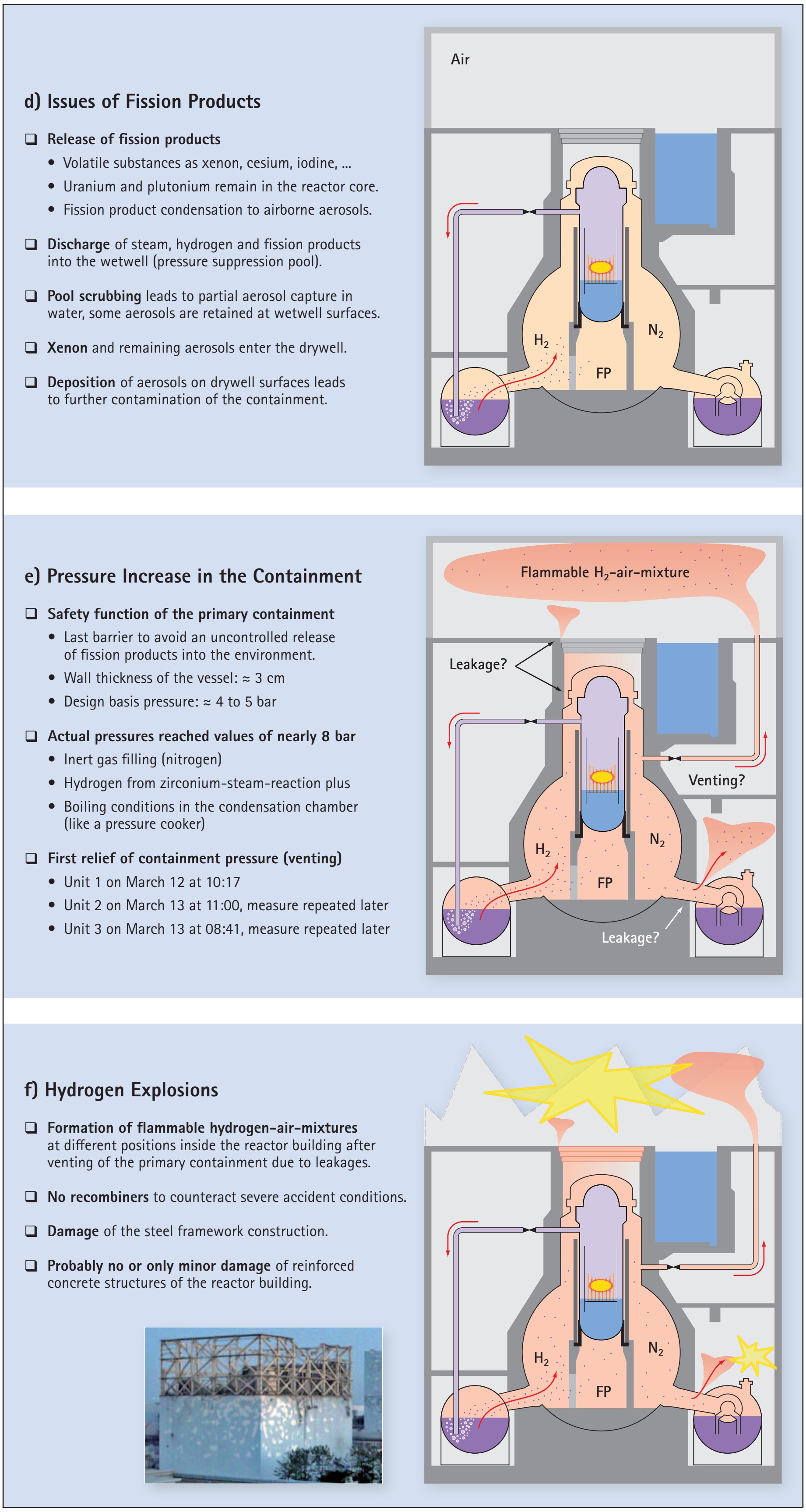

Fig. 6 d–f. *Development of the accident in the Fukushima Daiichi unit 1 [1].*

stored. The cooling water in the pool of unit 4 evaporated slowly within a couple of days after pool cooling had failed due to unavailability of the cooling pumps. Fuel assemblies ruptured and released their noble gases and volatile fission products to the atmosphere. However, photos taken from the pool later (mid-May) show that the racks and the assembly heads seem to be still intact, indicating that refilling of the pool prohibited large-scale melting (see *Figure 7*). Nevertheless, an explosion very similar to the ones in units 1 and 3 took place also in unit 4. *Tepco* meanwhile attributes this explosion to hydrogen having been carried over from unit 3 through a common venting pipe. In the meantime the integrity of the spent fuel pool of unit 4 seems to be questionable, as water was reported to be leaking from the pool and additional steel girders had to be installed beneath the pool as a precautionary measure against possible further earthquakes.

In units 5 and 6, fuel assemblies were in the reactors as well as in the spent fuel storage pools. Sufficient cooling could be maintained in both units.

Media focussed on the further development in unit 3, because its spent fuel pool contained a total of 32 Uranium-Plutonium-mixed oxide (MOX) fuel assemblies, which had been in operation some years ago. From a radiological point of view, there are hardly any differences between MOX and uranium fuel assemblies. With extended burnup, both types reach similar residual plutonium contents (MOX by burning plutonium, uranium assemblies by converting uranium into plutonium during normal operation). The main difference lies in a higher Americium content of MOX, while Americium is more volatile than Plutonium.

In the following days, endeavours were made to fill up the spent fuel pools of units 1, 3 and 4 with the aid of helicopters dropping seawater on the units. Later, fire brigade, police and military services with water cannons were also employed. The most sustainable option turned out to be Putzmeister concrete pump cars with elevation heights of up to 70 m, partly delivered from the USA and Germany by Antonov airlift (see *Figure 8*).

In parallel, reactor cooling of units 1 to 3 was restored temporarily as far as possible with mobile pumps and seawater. Later, fresh water cooling was used following accident management procedures to avoid further clogging of the cores by salt, which could have further deteriorated heat transfer.

On 15 March 2011, also a fire broke out at unit 4 for unknown reasons. The fire occurred in the area of the spent fuel element cooling pool. It is likely that together with the explosion, it destroyed parts of the building structure allowing nuclides to escape into the atmosphere.

In parallel, intensive endeavours were made to install a new 1.5 km-long electric power line to restore power supply. Between 20 March and 2 April 2011, the plant was reconnected to the external power grid. The units were connected successively to the external grid, providing lighting to the control rooms first and as a prerequisite for re-commissioning instrumentation and control systems and emergency cooling

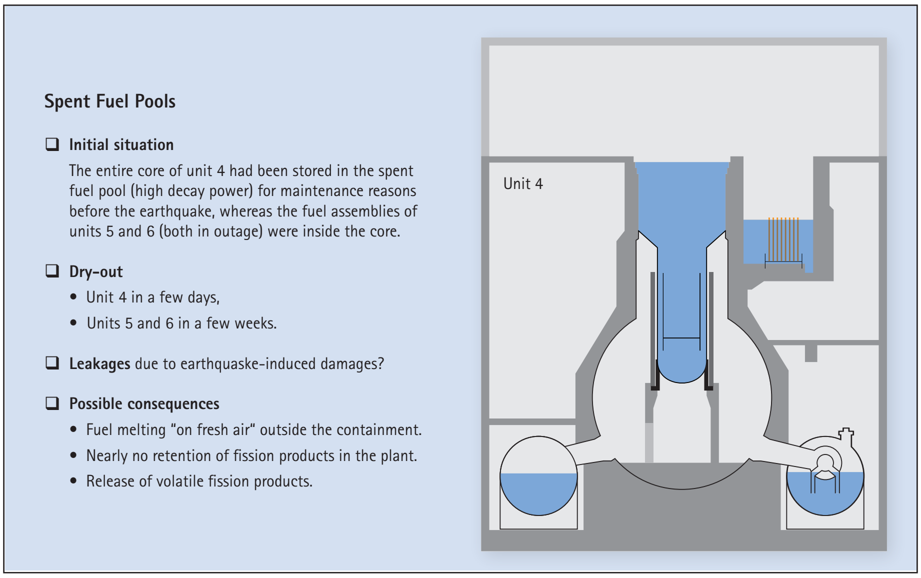

Fig. 7. Melting of fuel rods in the spent fuel pool of unit 4.

pumps. Due to the destructions caused by the tsunami wave and the explosions, electricity supply could not be switched on immediately to the power plant systems.

On 2 April 2011, highly radioactive water was found to leak from a crack of some 20 cm length into the ocean from the cooling water trench connected with the turbine building of unit 2. Different endeavours to stop the leakage, including filling the trench with concrete, were at first not successful. Finally, the leakage could be sealed by sodium silicate, also known as "liquid glass" on 5 April 2011.

All emergency measures aiming at the reduction of the consequences of the disaster were impeded by more or less strong after shocks with magnitudes up to 7.1.

Several times the rescue personnel had to be evacuated temporarily, because the local dose rates were too high.

Having secured both the reactors and the spent fuel pools in quasi-stable conditions, remediation measures were started in the following weeks including removal of debris, decontamination of the site, transferring the contaminated water from the turbine rooms into the ocean or to megafloat barges (unit 2) and inspection of the unit interiors by robots. The collected data indicate that all three cores have molten and may have been relocated at least partly.

When considering the individual aspects and "puzzle pieces" of the sequence of the accident, the personnel at the site deserves the maximum respect. It has to be born in mind that the region was hit by two severe natural disasters and also power plant staff was affected by extreme human affliction[4].

This consideration of the accident stops on 20 May 2011.[5] Therefore, the paper has to be considered as an "interim report", which will have to be amended as soon as further information may become available.

2.4 Accident-induced radiation load at Fukushima Daiichi

Figure 9 shows data on the release of radioactivity into the environment. The *Tepco* records for the period 12 to 30 March 2011, show an initial slight release of radioactivity during the first three days after the tsunami disaster, caused by e.g. deliberate venting of the primary containments of units 1 and 2. The first larger release was recorded in the morning hours of 15 March 2011, within the course of the explosions that occurred in units 4 and 2 and on 16 March 2011, from the already damaged unit 3. Peak values of local radiation dose rates were around 10 to 12 mSv/h with a tendency of first strong and then asymptotic decrease[6].

First measurement results about the contamination of the coastal waters were published on 26 March 2011. Accordingly, the Iodine-131 activity was quoted to be 80 Bq/l and the Cesium-137 activity amounted to 26 Bq/l[7]. According to Japanese safety authorities, these values exceed the permissible limiting values by a factor of 1,250. On 10 April 2011, *Tepco* ceased releasing water into the ocean.

On 11 April 2011, the Japanese government extended the 20-km-evacuation zone with individual adjacent areas where an annual radiation exposure of >20 mSv/a will have to be expected.

These are the known facts of the interim report about the severe accident in the *Fukushima Daiichi* nuclear power plant and the endeavours that have been made for more than a month to stabilise the situation and to bring it under control.

Table 2 shows a concise and brief presentation of the *Japan Atomic Industrial Forum (JAIF)* about the status of the plant on 25 May 2011 for all six units. In this table, the individual situations are commented by a green-yellow-red background. A larger section is also dealing with the environmental impacts yet to be determined.

Initially the Japanese authorities had classified the events in units 1, 2, and 3 caused by the tsunami as severe accidents of level 5 of the INES scale[8] (see *Figure 10*); on 12 April 2011, they reclassified the event because of the cumulated release of activity from all units to the highest level of INES-7. The total release of activity is estimated to be in the order of one tenth of the releases from the super-prompt power excursion in *Chernobyl* 1986, which was also classified as INES-7.

It can be ascertained that the radiation dose and damage in the region have been quite small due to the well-functioning tsunami early warning system (only

4 If, immediately after the tsunami, mobile emergency power generators would have been brought to the *Fukushima* site by sea or helicopter, this accident might have been probably far less devastating.

5 A minutes-like recording of events at the ***Fukushima Daiichi*** site for the period March 11 to 24, 2011, has been published with comments [2] on the basis of the information available.

6 For reasons of comparison: in Germany the natural radiation exposure amounts to approximately 2 mSv/a.

7 The half-life of I-131 amounts to 8 d, and of Cs-137 to 30 a.

8 *International Nuclear and Radiological Event Scale*, published by the *International Atomic Energy Agency, IAEA* in Vienna.

Fig. 8. A mobile concrete pump with a capacity of 120 t/h and a flexible, truck-type arm with a length of 58 m was used for about three hours in the late afternoon of 22 March 2011, to spray a total of 150 tonnes of sea water from the top onto the destroyed unit 4 and to fill the spent fuel cooling pool with water. This measure was repeated several times on the following days

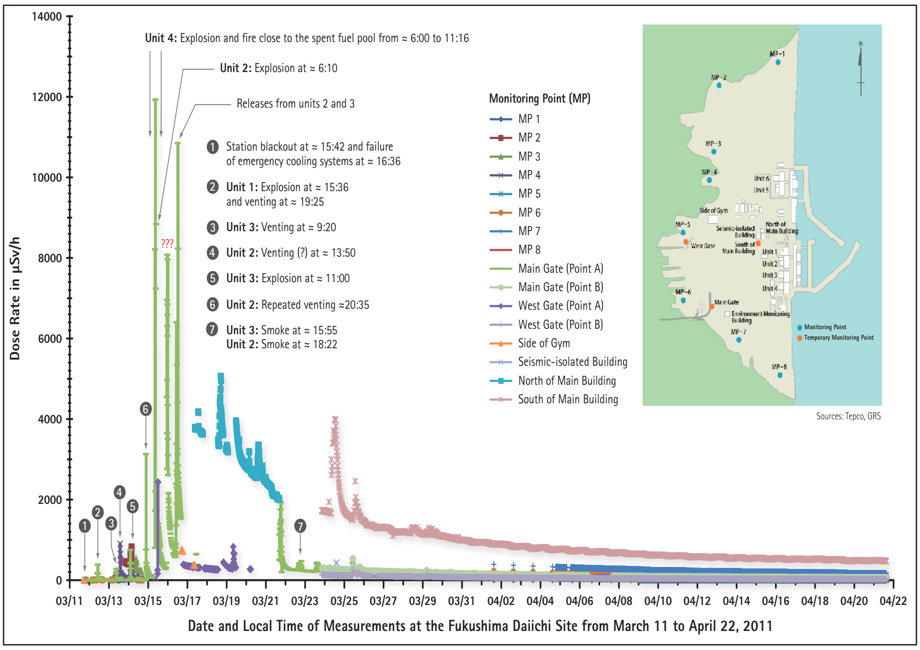

Fig. 9. Radiation exposure at the Fukushima Daiichi site.

Parameter	Status quo of nuclear power plant Fukushima Daiichi as of May 25, 2011					
	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6
Ines classification [1]	7 [2]			3	not specified	not specified
Core cooling system 1 [3]	inoperable			not necessary	operable	
Core cooling system 2 [4]	inoperable			not necessary	operable (cold shutdown)	
Reactor core						
• Number of fuel assemblies	400	548	548	0	548	764
• Fuel integrity	damaged			see spent fuel pool	not damaged	
• Water injection	continuing, switched from sea water to freshwater			not necessary		
Reactor pressure vessel						
• Structural integrity	limited damage, leakage	unknown		not damaged		
• Pressure	gradual rise	unknown		safe		
• Temperature	gradual decrease [5]	stable	gradual decrease			
• Water level	below bottom of fuel	fuel partially or fully exposed		safe		
Containment vessel						
• Structural integrity	damage and leakage suspected [6]			not damaged		
• Pressure	stable			safe		
• Water injection	started on April 27, 2011	planned		not necessary		
• Venting	temporarily stopped			not necessary		
Spent fuel pool						
• Number of fuel assemblies	292	587	514	1331	946	876
• Fuel integrity	unknwon		damage suspected	no severe damage [7]	not damaged	
• Cooling	water spray [8]	water injection [9]	water spray and injection [10]		recovered	
Reactor building	severely damaged [11]	partly opened	severely damaged [11]		vent hole on the rooftop [12]	
Main control room						
• Operability	poor due to loss of AC power				not damaged (estimate)	
• Lighting	recovered				not damaged (estimate)	

Safety significance according to the Japan Atomic Industrial Forum
severe high low

[1]) Ines: International Nuclear Event Scale [2]) estimation based on overall amount of radioacitity released at the Fukushima Daiichi site [3]) AC power, freshwater injection [4]) AC power, heat exchanger [5]) slight decrease after previous temperature rise to more than 400 °C on March 24, 2011 [6]) and leakages [7]) assumption based on video inspections carried out on April 28, 2011, some spent fuel rods may have been damaged based on radioactive substances detected in a water sample from the spent fuel pool [8]) continuing, freshwater [9]) continuing, switch from sea water to freshwater [10]) continuing, switch from sea water to freshwater, the water in the spent fuel pool of unit 4 had a temperature of about 83 °C before and 66 °C after the water spray and injection on March 23, 2011, a hydrogen explosion took place on March 15, 2011 [11]) due to hydrogen explosion [12]) deliberate measure to avoid a hydrogen explosion

Source: Japan Atomic Industrial Forum (Jaif)

Tab. 2. Status of the Fukushima Daiichi nuclear power plant on 25 May 2011 (source: Japan Atomic Industrial Forum).

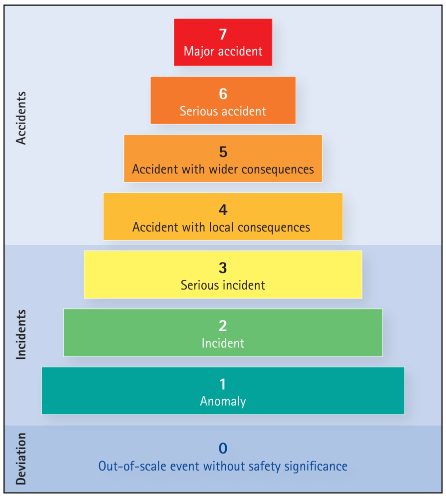

Fig. 10. INES scale to assess events in nuclear devices (source: IAEA).

55 minutes between earthquake and arrival of the tsunami at the *Fukushima Daiichi* site) and the favourable wind direction.

Two staff members each lost their lives at *Fukushima Daiini* (earthquake) and *Fukushima Daiichi* (drowning) due to the seaquake and/or the tsunami.

No staff member exceeded the annual dose rate that was elevated by the Japanese government from 100 to 250 mSv for nuclear power plant personnel. At the *Fukushima Daiichi* site, less than 20 staff members were exposed to doses between 100 and 180 mSv. Therefore, no immediate radiation-induced damage has occurred. The long-term risk to suffer from additional cancer diseases at 250 mSv is below one in a hundred.

2.5 Other sites

The other plants on the north-eastern Honshu coast *Fukushima Daini, Onagawa* and *Tokai* as well as the reprocessing facility *Rokkasho* were not affected by the tsunami as *Fukushima Daiichi* was, although being mostly also struck by the collapse of the regional power grids. In all cases reactors scrammed as designed and cooling could be maintained by diesels and/or availability of external power supply in time. Onagawa, although being situated much nearer to the epicentre, was not affected by the tsunami due to higher ground, but reported a fire, induced by the earthquake in a turbine room. It could be extinguished after hours.

Fukushima Daiini was also inundated, but only with a height of 2 to 3 m, and containment venting was at least prepared.

3 Final remarks

According to current information and findings, it can be ascertained that the decisive factor causing the disaster was the insufficient tsunami design basis. Therefore, the accident has not to be accounted for as a residual nuclear risk.

All power plant units at the above-mentioned four Japanese sites were hardly damaged by direct seismic impacts. The design basis for ground acceleration was exceeded by a maximum of some 25 % only at individual units and shutdown functions as well as emergency power supplies had worked according to design until the tsunami hit the coast.

Preliminary risk analyses reveal that at least the *Fukushima-Daiichi* plant design was based on the 100 to 1,000 year site flooding only. Tsunami statistics for all Japanese coasts (including the *Kuril Islands*) count 16 tsunamis with wave heights >10 metres over the last 500 years only (*Fukushima-Daiichi* design: 5.7 metres plus a reserve of 4.3 metres), i.e. Japanese coasts are hit by such a tsunami at least every 30 years.

The background of how this insufficient tsunami layout was not remedied over several decades was published in the *New York Times* on March 26 by *Norimitsu Onishi* and *James Glanz* "Japanese Rules for Nuclear Plants Relied on Old Science" (www.nytimes.com/2011/03/27/world/asia/27nuke.html?_r=1&hp).

The Japanese regulator *Nuclear and Industrial Safety Agency (NISA)* has meanwhile ordered all Japanese nuclear plants to check their inundation margin and to install if necessary water-tight doors on their safety-relevant buildings on short notice.

Additional information about the situation in *Fukushima Daiichi* and the region that reaches beyond the period of time considered within the scope of this paper can be obtained from WWW [3, 4 and 5].

In one of its next issues atw will report on the political and public reactions in Germany following the devastating accident in *Fukushima Daiichi* and the consequences for the 17 German nuclear power plants.

Acknowledgement

The authors would like to thank all experts – not all listed – for their comprehensive expertise and valuable critical remarks. The contributions by *Dipl.-Ing. Thomas Linnemann, VGB PowerTech,* and *AREVA* Erlangen are highly appreciated because of the spontaneous support granted when drafting the paper. This applies in particular to the figures that were transferred from the *VGB* paper [1] that is permanently being up-dated (www.vgb.org).

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[5] Results of the *KIT* working groups. http://www.helmholtz.de/kit-fukushima-folgen ■