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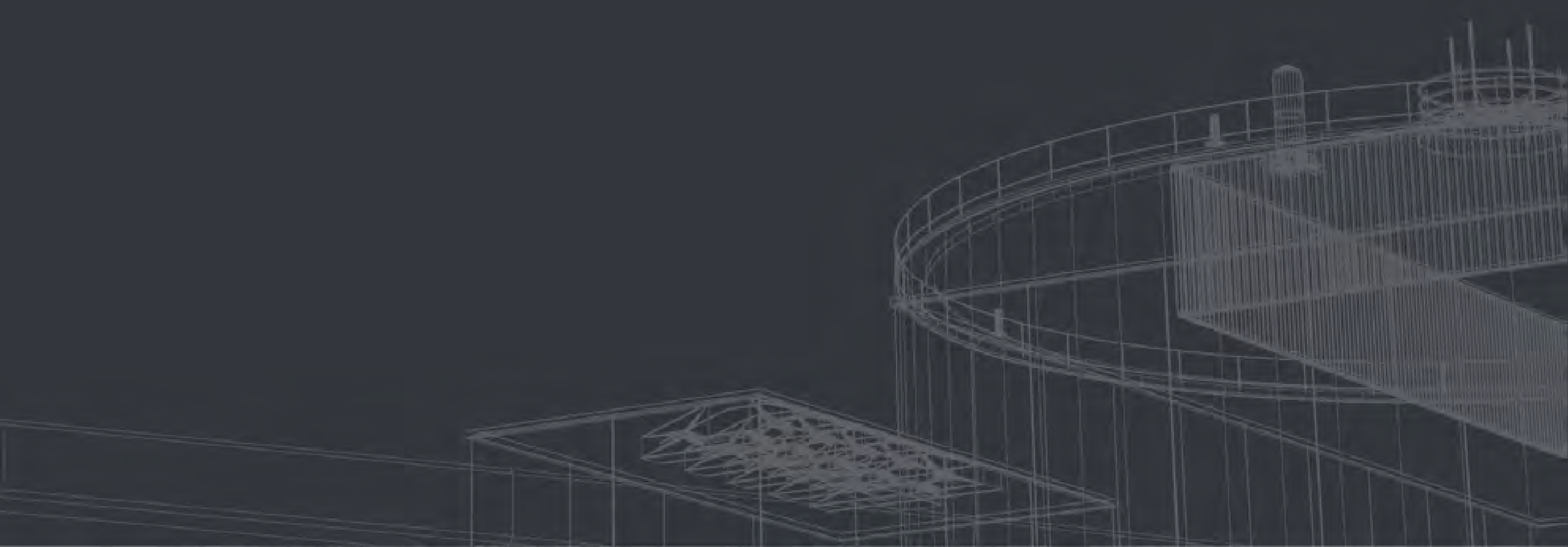
Event sequences Fukushima 11032011

Event sequences
in Fukushima Dai-ichi and Dai-ni following the Tohoku-Chihou-Taiheiyou-Oki earthquake on 11.03.2011



Fukushima

37° 25‘ 26.57“ N, 141° 1‘ 56.87“ E
11.03.2011

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1 Event series at Fukushima Dai-ichi

1.1 Event series in general

Before event occurrence, the following units of Fukushima Dai-ichi were in power operation

Unit 1
BWR/3, 1380 MW_{th} Mark I,
manufacturer: GE (1967 – 1971)

Unit 2
BWR/4, 2381 MW_{th} Mark I,
manufacturer: GE/Toshiba (1969 – 1974)

Unit 3
BWR/4, 2381 MW_{th} Mark I,
manufacturer: Toshiba (1970 – 1976)

on full power operation

Unit 4
BWR/4, 2381 MW_{th} Mark I,
manufacturer: Hitachi (1973 – 1978)

Unit 5
BWR/4, 2381 MW_{th} Mark I,
manufacturer: Toshiba (1972 – 1978)

Unit 6
BWR/5, 3293 MW_{th} Mark II,
manufacturer: GE/Toshiba (1973 – 1979)

undergoing maintenance, inspection or refitting (Unit 4, exchange of core shroud).

The operator of this unit is TEPCO (Tokyo Electric Power Company).

Figure 1:
View of Fukushima Dai-ichi, before/after;
source: TEPCO

Due to the Tohoku-Chihou-Taiheiyou-Oki earthquake on 11.03.2011 at 14:46 (magnitude M_W=9.0 (moment magnitude scale), an automatic reactor scram occurred in Units 1 – 3 (see Ref. 1). As a result of the earthquake, there was also a loss of off-site power (LOOP) and therefore, there was a loss of the auxiliary power supply. This led to containment isolation in Units 1 – 3 as well as the start-up of the emergency diesels (see Ref. 1). Due to this circumstance, the plants were in a state of loss of offsite power shortly after the earthquake. In spite of the high magnitude of the earthquake, the plants reacted, according to TEPCO (see Ref. 26), as per design.

On 11.03.2011 at 14:49, the Japan Meteorological Agency (JMA) issued a tsunami warning (see image 2). At 14:50, the first alert concerning the arrival and height of the tsunami was issued (Fukushima Pref. on 11.03.2011 at 15:10 expected a tsunami of a height of 3 m, see image 3; see Ref. 27). Later, JMA corrected the height of the tsunami (see Fig. 4).

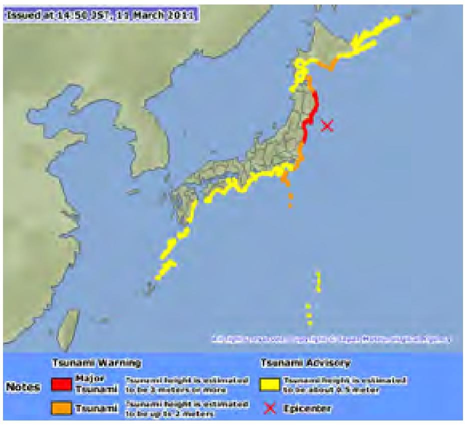


Figure 2: Tsunami warning 11.03.2011, 14:50; source: JMA

Tsunami Forecast Region	Estimated Tsunami Arrival Time	Estimated Tsunami Height
IWATE PREF.	(*1)	3 m
MIYAGI PREF.	15:00 JST 11 Mar	6 m
FUKUSHIMA PREF.	15:10 JST 11 Mar	3 m
CENTRAL PART OF PACIFIC COAST OF HOKKAIDO	15:30 JST 11 Mar	1 m
PACIFIC COAST OF AOMORI PREF.	15:30 JST 11 Mar	1 m
IBARAKI PREF.	15:30 JST 11 Mar	2 m
KUJUKURI AND SOTOBO AREA, CHIBA PREF.	15:20 JST 11 Mar	2 m
IZU ISLANDS	15:20 JST 11 Mar	1 m
EASTERN PART OF PACIFIC COAST OF HOKKAIDO	15:30 JST 11 Mar	0.5 m
WESTERN PART OF PACIFIC COAST OF HOKKAIDO	15:40 JST 11 Mar	0.5 m

Figure 3: Estimated tsunami height 11.03.2011, 14:50; source: JMA

Tsunami Forecast Region	Estimated Tsunami Arrival Time and Height						Observed Tsunami Arrival Time and Height of Initial and Maximum Tsunami			
	Issued at 14:49* JST 11 Mar (3 minutes after the earthquake)		Updated at 15:14 JST 11 Mar (28 minutes after the earthquake)		Updated at 15:30* JST 11 Mar (44 minutes after the earthquake)		Initial Tsunami		Maximum Height Tsunami	
	Estimated Tsunami Arrival Time	Estimated Tsunami Height	Estimated Tsunami Arrival Time	Estimated Tsunami Height	Estimated Tsunami Arrival Time	Estimated Tsunami Height	Observed Time	Observed Tsunami Height	Observed Time	Observed Tsunami Height
PACIFIC COAST OF AOMORI PREF.	15 : 30	1m	Arrival of tsunami confirmed	3m	Arrival of tsunami confirmed	8m	Hachinohe 15 : 22	(-) 0.8m	Hachinohe 16 : 57	4.2m or higher
IWATE PREF.	Arrival of tsunami inferred	3m	Arrival of tsunami confirmed	6m	Arrival of tsunami confirmed	10m or higher	Kamaishi 14 : 45 Miyako 14 : 48 Ofunato 14 : 46	(-) 0.1m (+) 0.2m (-) 0.2m	Kamaishi 15 : 21 Miyako 15 : 26 Ofunato 15 : 18	4.1m or higher 8.5m or higher 8.0m or higher
MIYAGI PREF.	15 : 00	6m	Arrival of tsunami confirmed	10m or higher	Arrival of tsunami confirmed	10m or higher	Ayukawa 14 : 46	(+) 0.1m	Ayukawa 15 : 26	8.6m or higher
FUKUSHIMA PREF.	15 : 10	3m	Arrival of tsunami confirmed	6m	Arrival of tsunami confirmed	10m or higher	Soma 14 : 55	(+) 0.3m	Soma 15 : 51	9.3m or higher
IBARAKI PREF.	15 : 30	2m	15 : 30	4m	Arrival of tsunami inferred	10m or higher	Oarai 15 : 15	(+) 1.8m	Oarai 16 : 52	4.2m
KUJUKURI AND SOTOBO AREA, CHIBA PREF.	15 : 20	2m	15 : 20	3m	Arrival of tsunami confirmed	10m or higher	Choshi 15 : 13	(+) 0.5m	Choshi 17 : 22	2.4m

Figure 4: Comparison of height - estimated and measured; source: Ref. 43

On 11.03.2011 at 15:27, the first tsunami reached the plant site. At 15:35, parts of the plant site were flooded by the second tsunami (see Ref. 44). This led to the destruction of the infrastructure and the equipment as well as to the loss of the ultimate heat sink (see Ref. 1) and a common-cause failure (CCF) of the auxiliary service water supply and also the destruction of the circulating water structure. Furthermore, a common-cause failure (CCF) of the diesel generators and thus, the failure of safety-related electrical power-consumers was a direct result of the flooding. The diesel generators of Units 1 to 5 are all arranged on the lowest level of the turbine building. The failure of the water-cooled emergency diesels would also have occurred indirectly by the loss of cooling (circulating water structure).

The failure of the power source and subsequently, the failure of the diesel generators sets led to a total loss of AC power and thus to a station blackout (SBO).

On 11.03.2011 at 15:42, a state of emergency was declared at Fukushima Dai-ichi (see Ref. 44).

By means of photographs dated 11.03.2011 at approximately 15:57 it can be seen that the water had already withdrawn to a large extent from the plant site (see Ref. 31). This means that the flooding lasted for about 22 minutes.

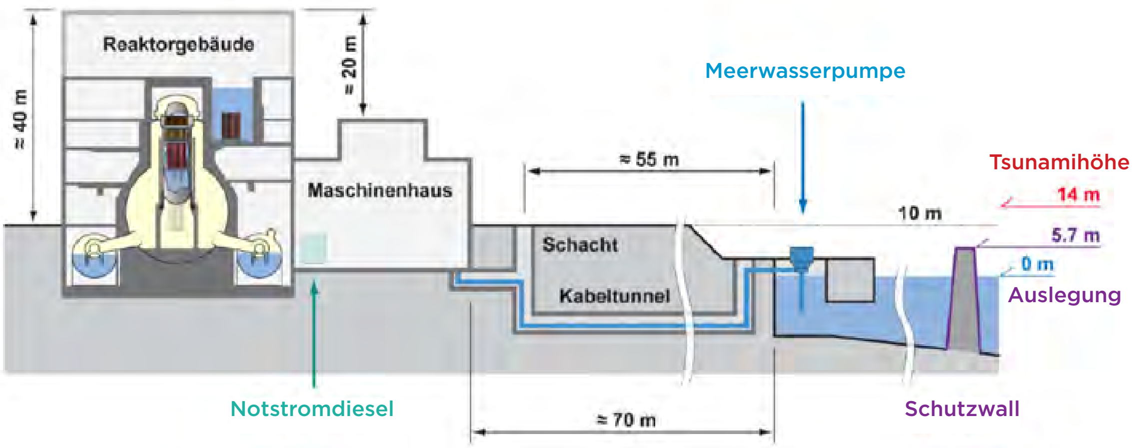


Figure 5:
Sectional view with heights above sea level, Units 1 – 4;
source: VGB

In 2002, the tsunami protection wall of Fukushima Dai-ichi had been raised from the original height of 3.1 m (design tsunami: Chile 1960 magnitude 9.3 m, height in Japan 3.2 m) to the maximum wave height of 5.7 m. It should be noted that the foundation level is set to 10 m resulting in an additional 4.3 m safety margin for the equipment located at that height.

After data evaluation of the on-site analysis, TEPCO reported that the RPV as well as the primary containments of Units 1 – 3 were damaged due to the accident (see Ref. 33 and Ref. 42). On 23.03.2011, the temperature in the primary containment of Unit 1 was still approximately 400° C (see Ref. 33).

Annotation 1
A diverse power source (off-site supply, external emergency power system, etc.) conducted via different cable routes could have minimised the consequences of the accident.

Annotation 2
A diverse water supply (wells, reservoirs, etc.) could have minimised the consequences of the earthquake.

Annotation 3
A secured physical separation within the circulating water structure could have minimised the consequences of the earthquake.

Annotation 4
A better flood protection of the emergency diesels and associated cooling systems could have minimised the consequences of the earthquake.

Annotation 5
The reviews conducted within the framework of the OSART- and WANO-missions should have detected the vulnerabilities in the plant.

There is no direct reference to the design within the framework of these reviews. However, the design and backfitting of the plant can be indirectly questioned when looking at various examples of "Operating Experience" (OE), for example in the IRS-reports (for example 7342 or 7788) in connection with the OSART missions or via the Significant Operating Experience Reports (SOER) about important operating experiences of the member companies in connection with the WANO missions. WANO member companies hold themselves accountable to specifically review the recommendations of WANO – SOER and to survey the actions where appropriate, derived from this review, while doing the peer reviews. This is an obligation within the operating company. However, there is no obligation to inform the public. It is slightly different within OSART since there is no formal obligation for the plant to implement all possible actions derived from the peer reviews in terms of safety. Within the frame-work of the periodic safety review, the state of the plant should be reviewed every 10 years. There are also different international procedures and standards. These three instruments together could enhance the safety level of nuclear plants within the framework of an obligatory, continuous process.

Figure 6:
Failure of cooling water supplies (Dai-ichi);
source: University of Japan

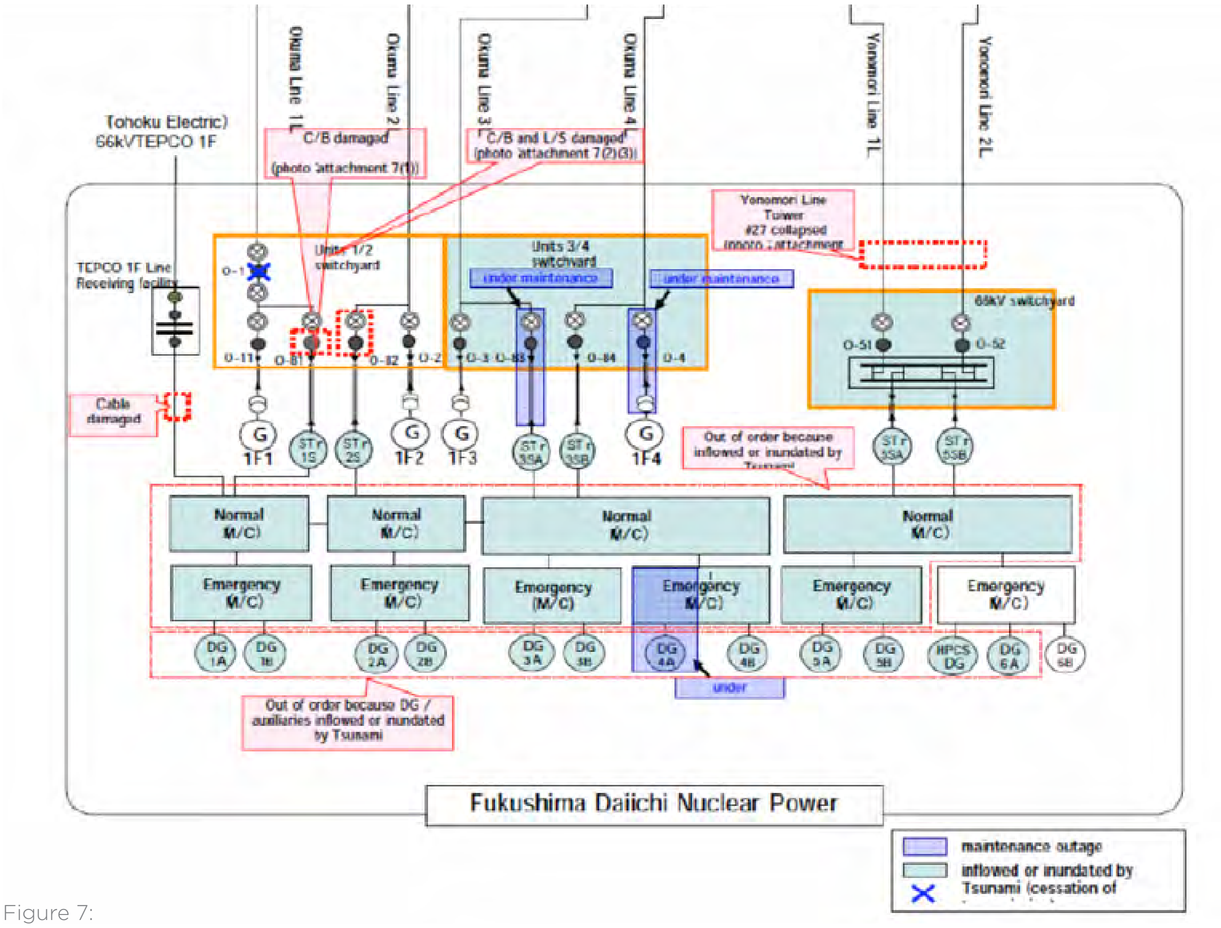


Figure 7:
Failure of auxiliary power supply (Dai-ichi);
source: TEPCO

1.2 Unit 1

1.2.1 Reactor

Following the tripping of the reactor (SCRAM) and the loss of offsite power (LOOP) at 14:47 in Unit 1 (see Ref. 44), residual heat was removed in accordance with the specifications using an isolation condenser (IC, Ref. 2), starting automatically at 14:52 (see Ref. 44).

Reactor core isolation cooling (RCIC) via the high-pressure coolant injection system (HPCI) was available for coolant make-up at decreasing RPV level (Ref. 44). Due to the high temperatures transients (a pressure drop from 70 to approx. 45 bar) approximately 10 minutes after the onset of the event, the isolation condenser was switched off manually at 15:03 (see Ref. 44) in order to ensure that the maximum cooldown gradient from $\Delta t > 55$ K/h met the prescribed standards. A train (Train A) of the IC was used for RPV pressure control. According to TEPCO, there was no loss-of coolant accident (LOCA) as a direct result of the earthquake. (see Ref. 26). This assumption was probably based on the severe drop in pressure.

As a consequence of taking the isolation condensers out of operation, there was an increase in pressure, with reactor pressure limitation at 60-70bar. The RPV was left on the high pressure path (hot shutdown) (Ref. 44). Therefore, the plants operated in the high pressure range and the required coolant injection took place via the HPCI. The reactor water level did not, however, reach the automatic actuation criteria (LL 148cm below the lower edge steam separator, see Ref. 43).

On 11.03.2011 at 15:35, the second tsunami damaged the circulating water intake, leading to the loss of the ultimate heat sink (mechanically). Additionally, there was a failure in the emergency power diesels (flooding), which lead to an electrical failure of the trains necessary for residual heat discharge to the ultimate heat sink (sea water cooling system), and at 15:37 a station blackout (SBO) occurred (see Ref. 43). Thus there was only the torus available for taking up the residual heat. (The isolation condenser had been taken out of operation manually and continued to be operated manually before the tsunami-induced flooding).

As a result of the simultaneous loss of the emergency power supply from Units 1 and 2 (diesel and interconnections), the standby from these units was also unavailable (see Section IV-39, Ref. 43).

Due to the unavailability of the signals in the control room, Tepco assumed a loss of function of HPCI. The signal of the valve position of the IC was also no longer showing (Ref. 44).

Owing to the continuing decay heat, the lost isolation condenser and the failed coolant injection, the RPV level began to drop, resulting in the uncovery of the fuel assemblies. The pressure was probably limited by safety relief valve (SRV) discharging into the pressure suppression pool (torus). More detailed information, however, is not currently available. This led to a temperature increase in the torus as a result of the decay heat yet to be removed, and as boiling point was reached, there was a pressure increase in the torus and drywell. Whether there was an automatic depressurisation of the RPV due to the low coolant level is currently unknown. Due to the disturbance or failure of the battery supply it is assumed that there was a fault in the instrumentation and control functions. (Failure of the strip chart recorder of the core monitoring system).

Annotation 6
It has to be clarified whether manual operation in the first 30 seconds was appropriate or not. The manual operation 'deactivation of the isolation condensers' caused the interruption of RPV pressure relief. The plant returned to the high pressure path. The aim in a radiological emergency must be to bring the plants into a state of low pressure where it is flooded and thereby able to be cooled. As the alert warning was of an estimated 3-m-high tidal wave (bearing in mind that the Fukushima Dai-ichi power plant is located on the border to the Maiyagi region, which had an alert of a 6-m-high tidal wave (see Ref. 27), there was no direct need for quick RPV pressure relief and RPV flooding. This would surely have lead to a less severe event sequence. The tsunami warnings of JMA were updated at 15:14 and 15:30 (see Fig. 4).

The connection to the power supply vehicle for battery support did not work straight away; access was made difficult by debris (see Ref. 6).

Annotation 7
It was not possible to carry out emergency actions immediately. The necessary power supply vehicles were available and ready for operation. One reason for the delay could be due to damaged switchgears. However, a lack of adequate emergency training could also be a reason as TEPCO arranged for training in this area for all the plants shortly after the accident (e.g. Dai-ni, see Ref. 41).

On 11.03.2011 at 15:50, the power supply of the instrumentation was lost (see Ref. 44).

On 11.03.2011 at 16:36, for approximately 10 minutes, there was a temporary failure in the monitoring of the RPV level (see Ref. 28). At 17:07, monitoring of the RPV level was lost completely (see Ref. 44).

Annotation 8
The reason for the failure of the RPV level measurement could be due to the problems with the power supply. If the RPV level monitor had functioned again, the low level should have been noticed. It is not known whether a quick manual depressurisation of the RPV was executed. As the RPV level at this point must have already been low, pressure relief should have been carried out according to the procedures. Emergency procedures should be in place for the case that electrical actuation of the safety relief valves SRV is no longer possible. Pressure relief is necessary for the emergency measure 'external water supply'.

On 11.03.2011 at 17:12, the emergency team discussed an alternative water supply to the RPV via fire protection lines of the firefighting system into the core spray system. At 17:30, a diesel-powered fire pump was available as stand-by, the associated valves of the core spray system were set manually. RPV injection is possible from a pressure of approximately 6.9 bar (see Ref. 44).

On 11.03.2011 at 18:18h to 18:25, one train (A) of the isolation condenser was opened (see Ref. 44).

On 11.03.2011 at 20:07 the RPV pressure was measured locally as being 69 bar (see Ref. 44).

On 11.03.2011 at 20:49, lighting in the main control room was temporarily re-established (see Ref. 44).

On 11.03.2011 at 21:00, stand-by water supply (to the RPV) with more fire-fighting pumps was established (see Ref. 6).

On 11th March 2011 at 21:19h, the DC supply to the RPV level measurement was temporarily available, at the point in time the level display showed +200mm above the top of active fuel (see Ref. 44).

On 11.03.2011 at 21:30, one train (train A) of the isolation condenser was opened (see Ref. 44). It is not completely clarified if this measure was sufficiently effective. According to the JAIF Earthquake Report dated 18.08.2011 the IC was manually shut down approx. 5 hours after the event without the lead engineer knowing (see Ref. 47).

On 11.03.2011, TEPCO assumed that at 21:40 the level reached top of active fuel and that at around 22:30h, first core damage would have to be expected (see Ref. 6). Based on this assumption, the government ordered the 2-km evacuation zone around Unit 1 of the Dai-ichi plant on 11.03.2011 at 20:50. (see Ref. 3). According to new assessments (see Ref. 33), the level reached the top of active fuel as early as 3h after SCRAM at approx. 17:50 and the bot-tom of reactor core 4.5h after SCRAM at approx. 19:20.

On 11.03.2011 at 21:33, as a result of the events in Unit 1, the government ordered the establishment of a 3-km evacuation zone and advised the population within a 10-km zone around the Dai-ichi plant to stay indoors (see Ref. 3).

Annotation 9

Why the injection of water into the RPV with an additional coolant could not be initiated has not been completely clarified. At this point in time (approximately 5hrs after the plant was flooded), all the necessary supplies had already failed. In addition, a quick repair of the power supply and water cooling systems was not possible for the time being (flooding of emergency diesels, damage to the circulating water building). Moreover, contrary to the measure of containment venting, it was probably the operator's responsibility to execute these actions.

On 11.03.2011 at 21:51, entering the reactor building was prohibited due to high local dose rates. At 23:00, the local dose rate was measured at 1.2 mSv/h in the turbine hall room at the entrance to the reactor building (double door, northern side, 1st floor; Ref. 44).

On 11.03.2011 around midnight and in the early morning of 12.03.2011, several power supply vehicles from different power plants arrived (see Ref. 44). As a result of traffic jams and the damaged roads and infrastructure, a delay was caused in the arrival of several high- and low-voltage supply vehicles. Attempts to transport the machines with army helicopters failed due the weight of the auxiliary equipment (see Ref. 44).

On 11.03.2011 at 00:49, the pressure build-up began in the primary containment (according to Ref. 44 the pressure in the drywell (DW) at this point in time was >6 bar_{abs} (11.03.2011 at 23:50). This took place approximately 7 hours after the flooding by the tsunami. At this point in time, the decay heat was still approximately 0.8 % of the thermal rated power of 1380 MW. There was no RPV cooling. The decay heat was probably led directly into the pressure suppression pool (torus) via the pressure relief valves. As heat removal from the torus to the ultimate heat sink of the sea was no longer a possibility, the pressure in the primary containment (drywell) rose continually. Also, as no coolant was injected into the RPV, the RPV level dropped.

The oxidation of the covered zirconium fuel rod cladding tubes of the fuel elements in vapour atmosphere resulted in the forming of hydrogen ($Zr + 2\ H_2O \rightarrow ZrO_2 + 2\ H_2$). During the equalisation of pressure, the hydrogen was transported via the torus into the drywell and accumulated in the area of the drywell head. Due to leakages, probably furthered by the high drywell pressure, the accumulation of hydrogen (H_2) took place in the reactor building (see also Ref. 43). The pressure in the drywell rose above the design pressure of 50-60 psig (approximately 3.45-4.14 bar, see Ref. 34). Presumably the drywell head failed. However, there is currently no conclusive proof of this.

On 12.03.2011 at 01:48 there was a failure of the diesel-powered fire pump (on stand-by). After refilling and changing of the starter battery, the re-start remained unsuccessful. The connection of fire engines to the fire water system was prepared. Owing to the destruction of a vehicle as a result of the tsunami and owing to the impossibility to drive along the connecting roads to Units 5 and 6, there was only one vehicle available at first (see Ref. 44).

The extreme high pressure in the primary containment that had reached approximately double the design pressure made the pressure relief from the primary containment (venting) necessary. This is necessary in order to prevent an uncontrolled overpressurisation failure in the primary containment.

On 12.03.2011 at 01:30, clearance for containment venting was requested from the prime minister, NISA and METI. Permission was given at 03:00 (see Ref. 44), with conditions on the part of METI and the task force headquarters with regard to the evacuation.

At a press conference at 03:06 h on the part of TEPCO, the preparation of filtered venting was announced (see Ref. 3). According to diagrams from NISA and JAIF, the pressure in the primary containment was already above design pressure and had reached levels between 6 and 8.4 bar (DW-pressure is confirmed at 8.4 bar at 02:30, see Ref. 44).

On 12.03.2011 at 05:00, it was ordered that full face masks with active carbon filters had to be worn by the staff in the control room. Due to the rising local dose rate in the control room of Unit 1, the control room staff was relocated to Unit 2 (see Ref. 44).

On 12.03.2011 at 05:44, the government decreed a 10 km evacuation zone around the power plant (see Ref. 3).

On 12.03.2011 at 08:03, the plant director announced the time set for the start of the venting for 09:00.

On 12.03.2011 at 09:04, 2 operators were sent to manually open the main valve upstream of the rupture disk (MO) to a degree of 25 %. This took place at 9:15. At 9:24, a second group was sent to open the "small" valve for pressure relief of the torus (AO90). Due to the high local dose rate (LDR), this work was stopped at approximately 9:30. In the scope of this preparatory work for the venting, one worker obtained a radiation dose of > 100 mSV (see Ref. 3). The manual opening on site was interrupted because of the high LDR. It was tried to open the valves from the control room with compressed air. Between 10:17 and 11:15, it was tried to open valve AO90 (see Ref. 44). Thereupon on 12.03.2011 at 14:00, a compressor for the pressure relief of the torus was connected in order to open the "large" valve AO72 (see Ref. 44).

According to Ref. 4 pressure relief was successfully carried out on 12.03.2011 at 14:30. According to Ref. 44, the pressure of the drywell decreased from 7.5 bar to 5.8 bar. The reason for the relatively long time difference between the preparation and the starting of the venting is partially technical (preparing, obtaining materials, exercising) as well as administrative (evacuation, communication, clearance).

Annotation 10

The venting system at the GE plants is designed as an "active" system. Auxiliary power is needed to open the valves. Due to the effects of the flooding, auxiliary power no longer existed. Due to the high activity (this also applies for the loss-of-coolant within the drywell), manual opening became problematic. Presumably, there were no measures for the reduction of radiation exposure for the on-site options to open the venting valves manually. Apparently, a sufficiently dimensioned recombiner for the case of a core meltdown did not exist. Even if it had existed, (electrical) auxiliary power would presumably have been required.

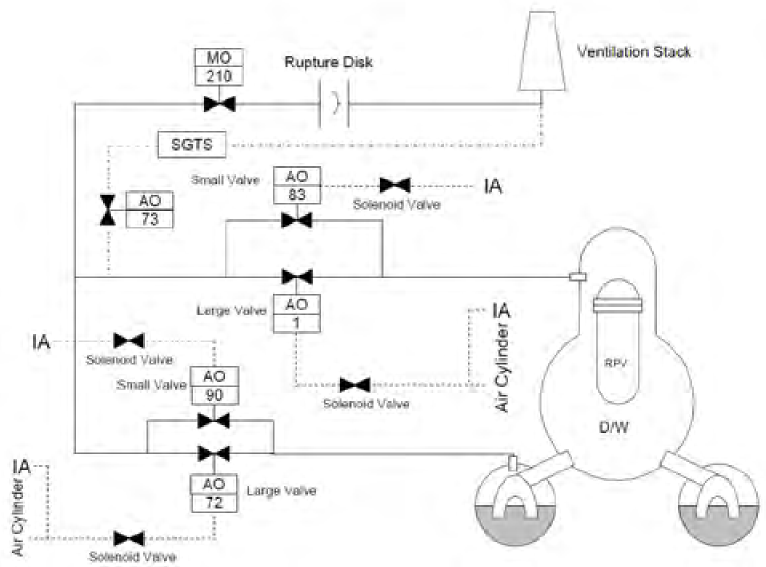


Figure 8:
Diagram of the venting system of Unit 1;
source: Ref. 43

According to TEPCO (see Ref. 44), up until 12.03.2011, 14:53, approximately 80,000 litres of freshwater were injected into the reactor via the fire extinguishing line and a mobile pump. This volume does not cover the refill volume required for residual-heat removal.

On 12.03.2011 around 15:30, the power supply of the emergency borating system (high-pressure system) was established via the connection of a power supply vehicle to the high voltage distribution of Unit 2. At 15:36, the preparation of water injection via the emergency borating system was completed (see Ref. 44).

On 12.03.2011 at 15:36, a hydrogen combustion occurred in the upper part of the reactor building, damaging the building structure. At this moment it is not clear how the combustion of the hydrogen in the reactor building occurred. It is assumed that an aftershock (see Ref. 5) triggered sparks that led to the ignition of the hydrogen. Another option for the ignition source might have been the re-established power supply (short-circuit, overvoltage) of the emergency borating system.

The detection of caesium on the plant after venting (12.30.2011 at 14:49, see Ref. 1) as well as the increase of the dose rate after the explosion are evidence of the fuel damage or of core meltdown. Currently, TEPCO assumes that at approximately 6:50 on 12.03.2011 already, nearly all fuel assemblies were affected by the core meltdown (see Ref. 10). According to the latest assumptions (see Ref. 33), all fuel assemblies melted 16 hours after SCRAM. The melt gathered in the lower part of the RPV.

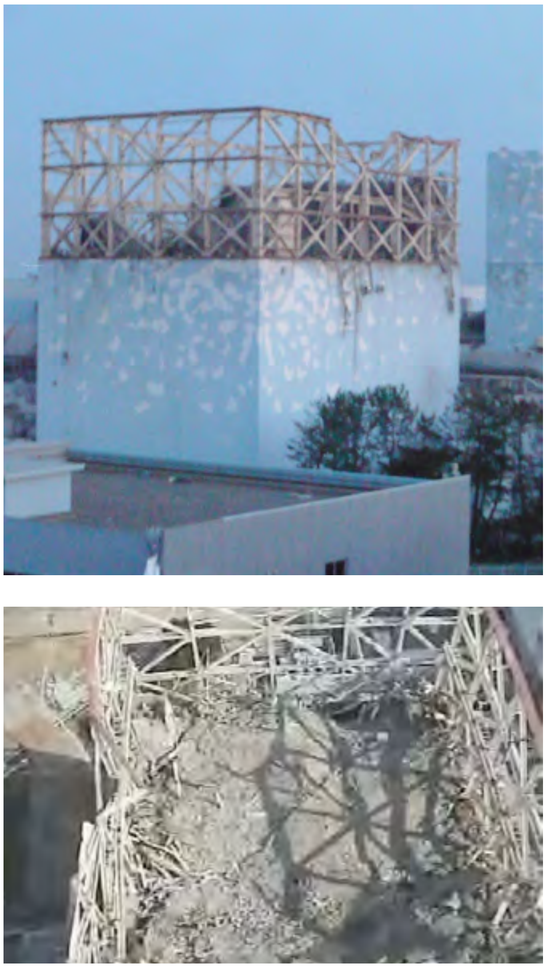


Figure 9:
View of Unit 1 after the hydrogen explosion; source TEPCO

On 12.03.2011 at 18:25, the evacuation of a 20-km radius around the plant and the instruction to shelter indoors within a 30-km radius was issued as a consequence of the hydrogen explosion and the increase of the local dose rate (see Ref. 1). According to Ref. 1, on 25.03.2011 the government advised the population within a 30-km radius around the plant to evacuate; this was however, their own decision.

On 12.03.2011 at 19:04, injection of sea water by means of three fire trucks connected in series (see Figure 10) began.

On 12.03.2011 at 20:45, the injection of borated sea water was started by means of the fire-fighting pipes in the RPV (see Ref. 3). Currently, it is not clear why there was a relatively long time lag between the readiness for injection and the start of the injection. It is believed that this time lag was due to administration and that sea water injection was started on 12.03.2011 at 20:05, after the issue of a directive on 12.03.2011 at 19:55 (see Ref. 3) and its release by the Nuclear and Industrial Safety Agency (NISA). Due to insights gained from Ref. 43 and Ref. 44, sea water injection was conducted without a regulatory directive. According to Ref. 43, this is attributed to insufficient communication. Currently, it is unknown whether sea water injection is part of the Severe Accident Management Guidelines (SAMG).

Annotation 11
The long time lags concerning the ‘water injection’ and delay during ‘venting’ cannot be fully explained. If this was due to the long decision-making process, it is to be checked how decision-making is regulated in ‘extreme situations’. At what point are the employees on site allowed to make their own decisions? How can it be ensured that decisions are made in sufficient time?

On 20.03.2011, the auxiliary power supply could be restored via Unit 2 (see Ref. 40). Permanent lighting in the control room was restored on 24.03.2011 at 11:30 (see Ref. 12). From the point of view of defence in depth, there are the following essential events in Unit 1:

- The need for manual interventions in safety systems 10 min after the occurrence of the event needs to be questioned. The 30 min-criterion is the international standard (from the TMI-event of 1979, no operator intervention before 30 minutes).

Figure 10:
Fire trucks for sea water injection;
source: Ref. 44

- Loss of offsite power and sustained ‘high pressure mode’ (the goal is to get the plant into shutdown cooling mode and not to remain ‘hot standby’). A standard simulator training program includes the loss of offsite power and also the station blackout scenario. We currently do not know what kind of training programs and curricula exist in nuclear power plants in Japan. Furthermore, it is unknown to us whether TEPCO has plant-specific simulators for its nuclear power plants.

- Flooding by the tsunami – beyond-design-basis event.

- After the flooding of the plant, essential and correct emergency actions were taken or prepared. Shortly after the flooding, the battery supply was ensured and the injection into the RPV was prepared 6 hours after the event happened. There were many problems during the carrying-out of the emergency actions taken to connect the ‘power supply vehicles’. The injection into the RPV could not be sufficiently carried out before the top of active fuel was reached although the loss of the ultimate heat sink (nuclear auxiliary service water) and the total loss of the emergency diesels must have been known to every-one at this point in time.

- Pressure build-up in the primary containment occurred due to the lack of coolant injection and the heat removal that was still required as a result of the decay heat and metal oxidation. Again, as in the case of the water injection, there were delays until the venting was carried out.

This means that 3 technical and organisational barriers in the framework of defence in depth for the prevention or minimisation of accident consequences failed after the flooding the plant. Currently, we do not know to what extent cross-functional actions that are due to the ‘multi-unit plant’ (shift, emergency team, maintenance) may have been crucial. The indepth analysis was performed in the framework of an interim report about the Fukushima events (see Ref. 47).

1.2.2 Spent Fuel Pool

Caused by the station blackout, loss of cooling for the spent fuel pool occurred in Unit 1. Following the hydrogen combustion event on 12.03.2011 at 15:36 in the reactor building, the spent fuel pool was in direct communication to the outside environment. The lack of cooling caused an increase in the water temperature and a drop in the water level in the spent fuel pool due to evaporation. The last fuel exchange for Unit 1 took place from 27.09.2010 during the refuelling outage of 2010.

On 31.03.2011 from 13:03 to 16:04, freshwater was injected for the first time into the spent fuel pool by a truck-mounted concrete pump.

Nothing is known about the condition of the 392 FA and the spent fuel pool. It is also not clear whether parts of the loading machine or parts of the crane fell into the pool after the explosion or earthquake. Owing to the high masses of debris (Fig. 9), no conclusion on the present condition is possible.

1.3 Unit 2

1.3.1 Reactor

After the reactor SCRAM at 14:47 and the blackout caused by the loss of power, residual heatremoval was carried out, according to the design basis after manual actuation of the turbinedriven Reactor Core Isolation Cooling System (RCIC). This is a system operated by the steam generated in the reactor and does not need any AC power supply. Due to the signal 'reactor level high', the RCIC system shut down automatically and repeatedly. A water injection from the torus and from the cold condensate tank rendered the continuation of this operation mode possible until 14.03.2011 at about 12:00 (see Ref. 43). Then at 13:25, the loss of the reactor cooling function was reported (see Ref. 7).

On 11.03.2011 at 15:35, the tsunami caused the destruction of the cooling water inlet and thus the loss of the ultimate heat sink (mechanically). Moreover, the loss of the emergency power supply (by the flooding) caused the loss of the trains necessary for residual-heat removal to the ultimate heat sink (sea water cooling) as well as the station blackout (SBO). This meant that only the torus was available for residual-heat removal.

On 11.03.2011 at 15:39, 4 minutes after the second tsunami wave, the RCIC was manually actuated (see Ref. 44).

On 11.03.2011 at 20:49, lighting in the main control room was temporarily re-established. At 21:50, the coolant level in the RPV was measured as +3400 mm above the top of active fuel, then at 23:25 the pressure in the drywell was 1.41 bar_{abs} (see Ref. 44).

On 12.03.2011 at 02:55, it was confirmed that the RCIC was in operation, and priority of pressure relief was concentrated on Unit 1. According to Ref. 43, the coolant injection from the condensate tank was changed to injection from the torus. On 12.03.2011 at 17:30, the plant director ordered to start preparations for pressure relief (see Ref. 44).

On 13.03.2011 at 08:10, the main valve upstream of the rupture disk (MO271) opened up to 25 % (see Fig. 12). At 11:00, the 'large' valve (AO205) upstream of the torus was opened for pressure relief, thus pressure relief of the primary containment was actuated upstream of the rupture membrane. According to Ref. 44, the actuation pressure amounted to 4.27 bar (over-pressure), thus making it 5.28 bar_{abs}.

Caused by the failure or loss of the batteries, a failure in the I&C functions must be assumed (loss of the reactor core monitoring records). Moreover, particular attention must be paid to the RPV level records. As these are differential-pressure measurements, evaporations or sub-cooled boiling in the measuring pillars could be assumed. At present it is unknown whether diverse measurements (like reactor core internal temperature) were available.

It is essential to note that according to the information available, water was injected into the reactor pressure vessel (RPV). The amount of the water injected was insufficient.

Annotation 12
Problems with the signal displays during transients are not new. This was the reason to partly upgrade the in-core instrumentation of the reactor core internal temperature measurement. It is essential to know whether the accident management instrumentation was available and provided the necessary quality of the information.

On 14.03.2011 at 11:01, the explosion in Unit 3 caused the closure of the 'large' valve (AO205) upstream of the torus for the pressure relief as it had lost its actuation (pressurised air). Moreover, the explosion caused a loss of the prepared feed water injection line and damaged the necessary fire extinguishing vehicle (see Ref. 43 and Ref. 44). The drywell pressure amounted at that time to 4.5 bar_{abs} (3.5 bar overpressure).

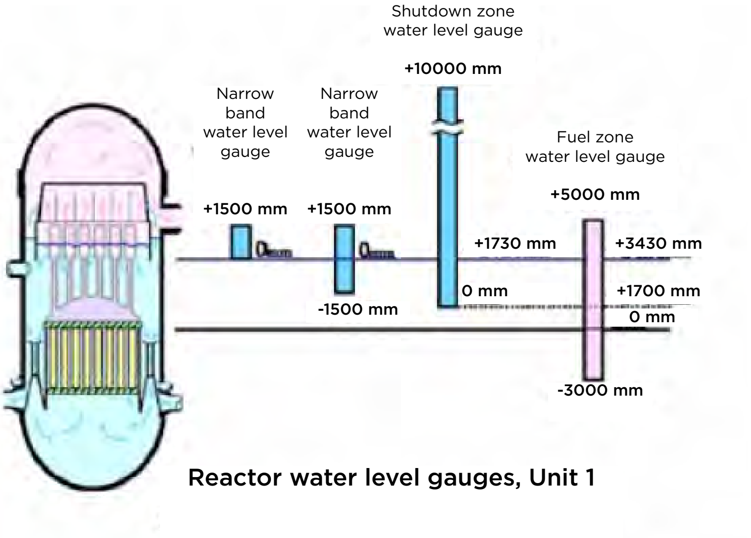
On 14.03.2011 at 12:30, the wetwell pressure (in the torus) amounted to 4.86 bar_{abs}, the temperature in the torus amounting to 149.3 °C (see Ref. 44).

On 14.03.2011, in order to avoid a hydrogen explosion, preventive openings were made in the roof of the reactor building (see Ref. 3).

After the loss of reactor cooling and coolant supply at 13:25, it was estimated that coolant level would reach 'top of active fuel' at 16:30 on 14.03.2011. It was in fact reached at 17:17 (see Ref. 44).

On 14.03.2011 at 16:34, after RPV pressure relief, arrangements for sea water injection into the RPV began (see Ref. 1).

Due to the RPV pressure relief at 18:03 (60.7 bar), RPV pressure decreased until about 19:03 up to 6.3 bar (see Ref. 44), while the RPV level dropped to -3700 mm below the



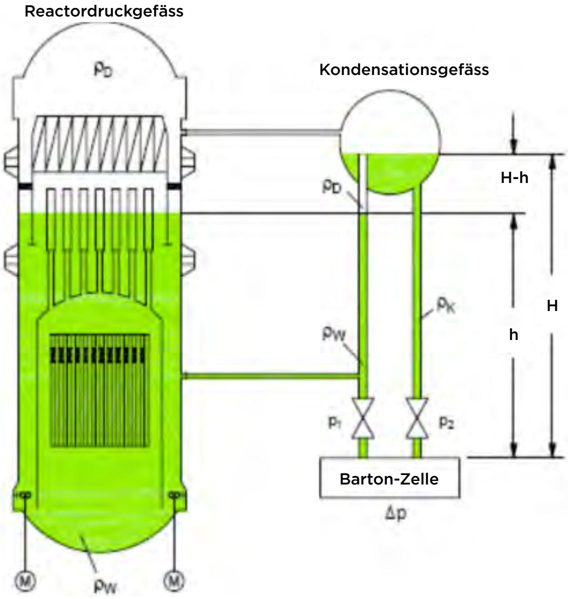


Figure 11:
Fill level records, BWR Example Unit 1;
source TEPCO

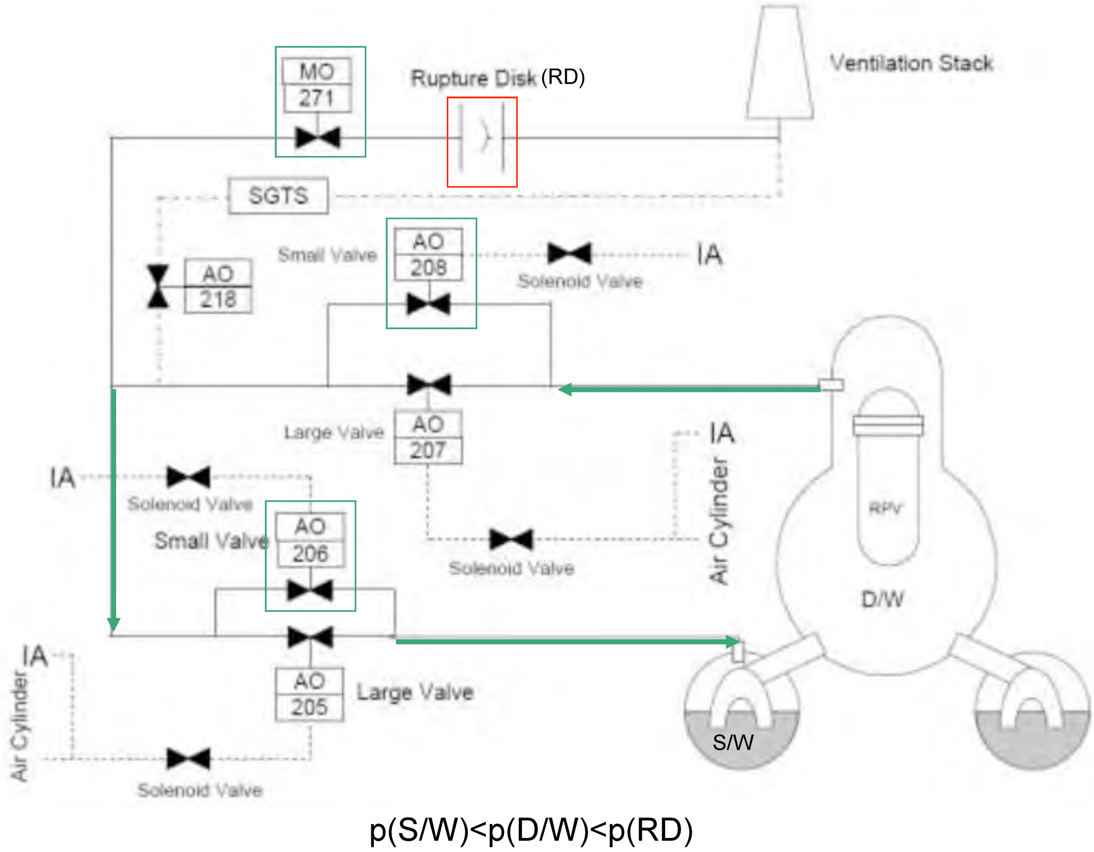


Figure 12:
Venting system of Units 2 and 3;
source: Ref. 43

top of active fuel at 18:22 (see Ref. 43), and a significant pressure increase occurred in the primary containment (drywell).

On 14.03.2011 from 19:20 until 19:54, the loss of the sea water injection to the RPV occurred due to a lack of diesel fuel of the fire extinguishing vehicle (see Ref. 44). In the time from 13:25 until 19:54, no coolant injection to the RPV took place for about 6 hours. According to the assessment of the IAEA, the coolant level in the RPV probably reached the core bottom level (bottom of active fuel – BAF) about 76 hours after the tsunami (see Ref. 46).

On 14.03.2011 at 21:00, the 'small' valve (AO206) upstream of the torus was opened to relieve pressure (see Ref. 44). In the period between 21:20 and 22:50, RPV pressure relief was again carried out by safety relief valves (SRVs). The drywell pressure was lower at 22:50 than the actuation pressure of the rupture disk (4.27 bar as overpressure). The drywell pressure at that moment was stable within the range of 3 to 4 bar_{abs} (see Ref. 44).

On 15.03.2011 at 00:02, the 'small' valve (AO208) upstream of the drywell was opened for some minutes. According to Ref. 44 it was confirmed that the rupture disc was not open.

The drywell pressure remained at 7.5 bar_{abs} (see Ref. 44). Another attempt to relieve pressure at 03:00 was unsuccessful.

On 15.03.2011 at 06:14, a hydrogen explosion occurred within the reactor building. Due to the falling pressure in the torus afterwards, the explosion is assumed to have occurred in the area of the torus (see Ref. 3).

The root cause of the explosion is assumed to be the insufficient coolant supply, resulting in the fuel tubes oxidation in the reactor core. The released hydrogen was transported by the RPV pressure relief into the torus. The question if the torus had already been damaged by the harsh condensation (hot steam injection into the already boiling water), or if the torus was damaged by the explosion cannot be clarified at the moment. It must be assumed that still more hydrogen was forced into the torus due to the high pressure in the drywell and the rup-ture disk remaining closed or the valve (MO271) upstream of the rupture disk remaining closed (see Fig. 12). Should the valve MO271 have remained closed, a failure of the pipe, caused by the overpressure with following hydrogen combustion, could have been the cause of the explosion.

On 15.03.2011 at 11:25, the drywell pressure amounted to 1.55 bar_{abs} (see Ref. 44).

On 20.03.2011 at 15:46, it became possible to re-establish the off-site power supply (see Ref. 35).

On 20.04.2011, an inspection of the site by robots found a high temperature and humidity within the reactor building (see Ref. 29), which could have been caused by the damage of the torus (see Ref. 3).

Annotation 13
The insufficient coolant replenishment suggests insufficient coolant injection. The question whether the necessary water injection amounts were specified in the Severe Accident Management Guidelines (SAMG) or how they were verified is yet unknown. Moreover, it is .

Annotation 14
The long delay prior to ‘venting’ is not clearly explainable. If it was due to the long decision-making process, it must be checked how the decisions are made in ‘emergency’ situations. At what moment can the personnel make their own decision? When are the authorisations by other persons responsible necessary? How is it ensured that decisions will be made in due time?

1.3.2 Spent Fuel Pool

The station blackout (SBO) caused a loss of coolant supply for the spent fuel pool at Unit 2. Due to the decay heat of the fuel, water temperature in the spent fuel pool increased and the level dropped. The last fuel exchange for Unit 2 took place starting on 18.11.2010 during the refuelling outage of 2010.

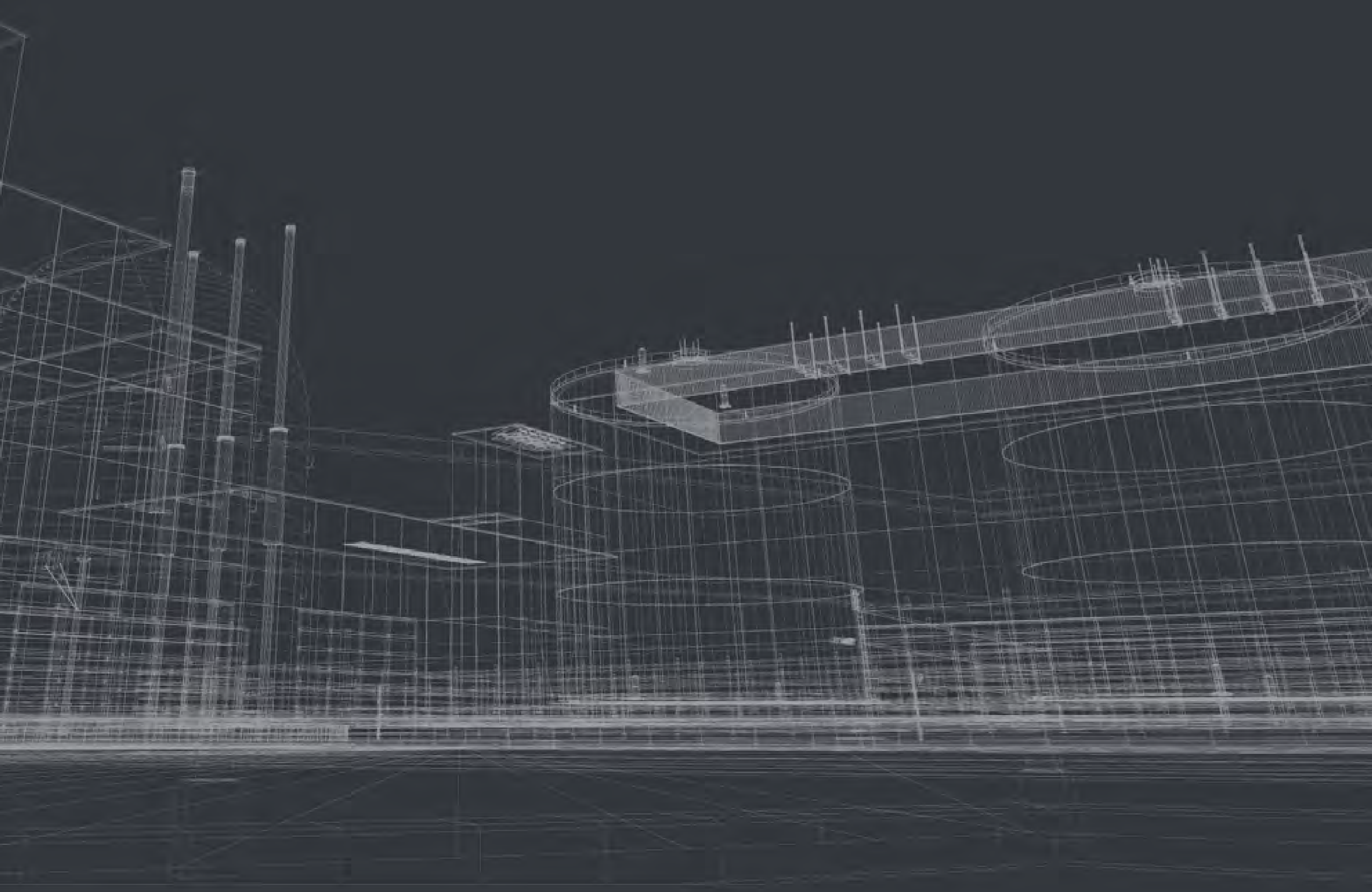
On 20.03.2011 beginning at 15:05, sea water was injected for the first time into the spent fuel pool via the coolant line. From 29.03.2011, this was changed to fresh-water injection (see Ref. 3).

On 16.04.2011, water samples were taken from the spent fuel pool of Unit 2. The samples indicated nuclides of I-131, Cs-134 and Cs-137 (see Ref. 30). It is yet unknown if the presence of these nuclides can be put down to the damage of the fuel. Nothing is yet known about possible damage of the spent fuel pool or.

Annotation 15
The insufficient auxiliary water supply leads to the conclusion that the injection amounts were insufficient. It is unknown whether the appropriate water injection amounts are specified in the Severe Accident Management Guidelines (SAMG) and how they were verified. Moreover, it is unclear if sufficient material for the necessary accident management was in place at the site. It is unclear whether the necessary measuring displays (like pool temperature, coolant level) were available.

Fukushima

37° 25‘ 26.57“ N, 141° 1‘ 56.87“ E
11.03.2011



1.4 Unit 3

1.4.1 Reactor

After the reactor scram (SCRAM) at 14:47, the main turbine was manually shut down (see Ref. 44). Due to the station blackout caused by the loss of off-site power, residual-heat removal from Unit 3 was carried out as per design by the manually actuated reactor core isolation cooling system (RCIC) and then by the high-pressure coolant injection system (HPCI). Actuated by the signal “reactor level high“, the system RCIC repeatedly shut down automatically.

On 11.03.2011 at 15:35, the tsunami caused the destruction of the cooling water inlet and thus the loss of the ultimate heat sink (mechanically). Moreover, the loss of the emergency power supply (due to flooding) caused the loss of necessary residual-heat removal trains to the ultimate heat sink (sea water cooling) as well as the station blackout (SBO) at 15:38 (see Ref. 43). This meant that only the torus was available for residual-heat removal.

On 11.03.2011 at 16:03, the RCIC was manually actuated. On 11.03.2011 at 21:58, lighting in the main control room was temporarily re-established. On 12.03.2011 at 11:36, the RCIC shut down automatically; while the HPCI started up automatically at 12:35, actuated by the low level in the RPV (see Ref. 44).

On 12.03.2011 in the time between 12:30 and 19:00, the reactor pressure decreased by more than 60 bar and became stable at about 10 bar (see Ref. 43). It is assumed that due to the strong pressure decrease, a fresh steam leak occurred in the HPCI system (see Ref. 43).

Due to the residual-heat removal to the torus and after the loss of the function ‘pressure relief to the torus’, the pressure in the primary containment increased. TEPCO began preparations for the pressure relief from the primary containment (see Ref. 4).

On 12.03.2011 at 17:30, the plant director gave the instruction to begin arrangements for pressure relief (see Ref. 44).

On 13.03.2011 at 02:42, the HPCI shut down and at 05:10, TEPCO announced that all injection functions had been lost (see Ref. 8). In the time between 02:30 and 04:00, the pressure in the RPV increased from about 10 bar up to about 70 bar. The assumption of a fresh steam leak in the HPCI system was confirmed by a new pressure increase in the RPV.

From then on, pressure relief was only via the SRVs. At the moment of the loss of the HPCI, no level signals were available. At 03:51, DC power was re-established for the instrumentation, with the coolant level being signalled -1600 mm below the top of active fuel – TAF) (see Ref. 43).

TEPCO estimated that the RPV coolant level would reach the top of active fuel at 04:15 on 13.03.2011 (see Ref. 44). According to Ref. 45, the level dropped below the top of active fuel at about 08:00.

On 13.03.2011 at 05:15, the plant director gave the instruction to start arrangements for pressure relief up to the rupture disk (see Ref. 44). At 05:23, the ‘large’ valve AO205 was to be opened for pressure relief in the torus; however, while the necessary auxiliary energy (pressurised air) was not available. Following the switch-over of the pressurised air tank, it became possible to open the valve (see Ref. 44).

On 13.03.2011 at 07:39, the containment spray function was actuated (see Ref. 44). At 08:35, the main valve MO271 upstream of the rupture disk opened as per design by 15 % (see Ref. 44). On 13.03.2011 at 08:41, the arrangements for the pressure relief of the primary containment (drywell) were completed (see Ref. 36 and Ref. 44).

On 13.03.2011 at 09:20, after the manually actuated RPV pressure relief (at 09:08), the injection of borated freshwater (until about 12:20) and then injection of freshwater by the fire extinguishing line was initiated (at 13:12) (see Ref. 3 and Ref. 44). In the time between 02:42 and 09:20, i. e. for about 7 hours, no coolant injection into the RPV was in place (see Ref. 46).

On 13.03.2011 at 09:24, the drywell pressure dropped from 6.37 bar_{abs} (at 09:10) to 5.4 bar_{abs}, with TEPCO assuming successful venting (the rupture disk opened). Due to the pressurised-air leakages, valve AO205 closed, while after the switch-over of the pressurised-air tank, the valve could be reopened at 12:30. Due to the continuous relief by SRVs and the resulting high room temperature and strong vibrations in the torus, the valve could not be interlocked manually (see Ref. 44).

On 13.03.2011 at 15:28, a dose rate of 12 mSv/h was measured in the control room, the operators were evacuated to Unit 4 (see Ref. 44).

On 13.03.2011 at 17:52, a temporary compressor was connected to the pressurised-air supply. The compressor was inserted into the reactor building by a crane via the material airlock. Due to the decreasing pressure in the drywell (20:10), TEPCO assumes that the ‘big’ venting valve of the torus (AO205) could be opened by the compressor. After a renewed loss of the pressurised-air supply, the valve closed, and pressure in the dry-well increased from 2.65 bar (on 14.03.2011 at 02:00) to up to 3.15 bar (at 03:00) (see Ref. 44).

On 14.03.2011, in the time between 01:10 and 03:20 (see Ref. 3) the sea water supply had to be discontinued owing to the low level in the interim tank.

Despite the later continuing water injection, the level in the RPV dropped and the pressure increased. This was possibly due to an insufficient amount of water injected. Due to the high activity level in the drywell the core damage possibility was estimated as 30 % (see Ref. 43).

Annotation 16
The insufficient water supply led to the conclusion that the injection amounts were insufficient. It is unknown whether the appropriate water injection amounts are specified in the Severe Accident Management Guidelines (SAMG) and how they have been verified. Moreover, it is unclear whether sufficient material for the necessary accident management was in place at the site.

Annotation 17
The question whether the accident instrumentation was still available or whether the necessary quality of information was ensured cannot be clarified conclusively.

On 14.03.2011 at 05:20, preparations for the further pressure relief of the primary containment began (see Ref. 36).

On 14.03.2011 at 06:10, the ‘small’ valve was opened to relieve the pressure in the torus (AO206). After a renewed loss of pressurised-air supply the valve closed, several attempts to open the valve were not successful (see Ref. 44). The pressure in the drywell amounted at 06:10 to 4.6 bar_{abs}, at 06:50 to 5.3 bar_{abs} (see Ref. 12) and at 09:05 to 4.9 bar_{abs} (see Ref. 43).

RPV pressure was periodically relieved by the Safety Relief Valves (SRVs) which brought about uncovery of the fuel and fuel cladding tube oxidation with subsequent hydrogen release.

Also, in this case, it is assumed that the hydrogen – via leakages from the drywell (e.g drywell head flange, penetrations etc.), favoured in turn by the high pressure in the drywell – accumulated in the reactor building.

On 14.03.2011 at 11:01 (see Ref. 3), a hydrogen explosion occurred in the reactor building which caused severe damage of the structures of Unit 3, the equipment of Unit 3 (the crane in the reactor building) as well as the external shell of Unit 4. It is still unclear what caused the combustion of the hydrogen accumulated in the reactor building.

11 persons were injured in the explosion (of which 4 were members of TEPCO staff, 3 were contract workers and 4 members of the military staff). Caused by the blast wave or flying debris, fire extinguishing vehicles were damaged and pipelines and hoses that were meant to supply sea water for injection were disconnected. Since then, debris with very high dose rates has been making the work even more difficult. Moreover, the explosion impaired the work at Unit 2 (like pressurised-air supply, venting see Section 1.3.1, Ref. 44).

On 14.03.2011 at 11:25, the reactor pressure increased according to Ref. 43, to 1.85 bar, the drywell pressure amounting to 3.6 bar and the pressure in the torus amounting to 3.8 bar.

1.4.2 Spent Fuel Pool

The station blackout (SBO) also caused a loss of the coolant supply for the spent fuel pool at Unit 3. The last refuelling for Unit 3 during the 2010 outage started on 23.09.2010. Due to the decay heat of the fuel assemblies, the water temperature in the spent fuel pool increased and the level dropped. On 16.03.2011 at 09:48, the water in the spent fuel pool was replenished for the first time by sea water dropped from a helicopter and later injected by water cannons (see Ref. 3).

Due to the severe damage of the reactor building and the resulting debris in the spent fuel pool (Fig. 13, see Ref. 18), mechanical damage of the fuel in the spent fuel pool must be assumed. The increase in the ambient dose rate (up to about 11 mSv/h) at the main gate or the western gate after the steam releases from the spent fuel pool on 16.03.2011 and 21.03.2011 (see Ref. 19) also indicates damage to the spent fuel. Nuclide analyses of 08/09.05.2011 indicate strong concentration of radionuclides (mainly Cs-134/137) in the spent fuel pool, as compared to the reference value of 02.03.2011 (see Ref. 37). This also indicates damage to the spent fuel.

Annotation 18
The insufficient auxiliary water supply led to the conclusion that the injection amounts were insufficient. It is unknown whether the appropriate water injection amounts are specified in the Severe Accident Management Guidelines (SAMG) and how they have been verified. Moreover, it is unclear if sufficient material for the necessary accident management was in place at the site. It is unclear whether the necessary measurement displays (e.g. pool temperature, water level) were available.

Figure 13:
Debris in the spent fuel pool, Unit 3;
source Ref.18

1.5 Unit 4

When the earthquake and the later Station Blackout (SBO) occurred, Unit 4 was in outage (since 29.11.2010) for an impending exchange of the core shroud. The RPV had been completely unloaded for the next core shroud exchange. For this, the entire fuel was stored in the fuel pool. The decontamination of the primary circuit had been completed.

Of the emergency diesel generators (DG) provided, one DG was shut down for maintenance, the second one was actuated automatically after the earthquake (see Ref. 43). Following the earthquake, all work and inspections at Unit 4 were suspended (see Ref. 43).

On 11.03.2011 at 15:35, the tsunami caused the destruction of the cooling water inlet and thus the loss of the ultimate heat sink (mechanical). Moreover, the loss of the emergency power supply (by the flooding) caused loss of the necessary residual-heat removal trains to the ultimate heat sink (sea water cooling) as well as the station blackout (SBO) at 15:38 (see Ref. 43). Due to the SBO, the cooling of the spent fuel pool failed. The decay heat of 1535 FA (max. pool capacity: 1590 FA – see Ref. 43) brought about a rise in the pool water temperature and a slow drop of the water level.

On 14.03.2011 at 04:08, according to the Ref. 3, the water temperature amounted to 84 °C.

On 15.03.2011 at 06:14, an explosion occurred in the reactor building of Unit 4 which caused damage to the building structures. The root cause of the explosion is yet disputed. It is hardly plausible to assume in this case, as it was with Units 1 to 3 that a hydrogen explosion occurred due to the oxidation of the fuel cladding tubes, taking into consideration the event progress and the amount of water present in the spent fuel pool. The assumption of the analysis team that the earthquake caused the damage to the fuel pool was refuted according to Ref. 9, in which TEPCO confirms the integrity of the spent fuel pool.

Figure 14:
Units 3 and 4 after the hydrogen explosion;
source: TEPCO

Hypotheses that the hydrogen could be accounted for by other sources, like the venting of Unit 3 (see Sec. 1.4.1) or surge lines of the ventilation of Units 3 and 4 at the bottom of the stack (see Ref. 10) or the generation of an explosive mixture from the welding and cutting gas (shroud dismantling) cannot be proven explicitly (see Ref. 43). More recent reports assume, however, that the hydrogen from Unit 3 could overflow via the common exhaust air line and the ‚emergency gas treatment plant' of Unit 4 into the upper part of the reactor building of Unit 4 (see Fig. 15). Apparently, the 'emergency gas treatment plant' does not possess any non-return valves to prevent such overflow (see IV-90/IV-96, Ref. 43).

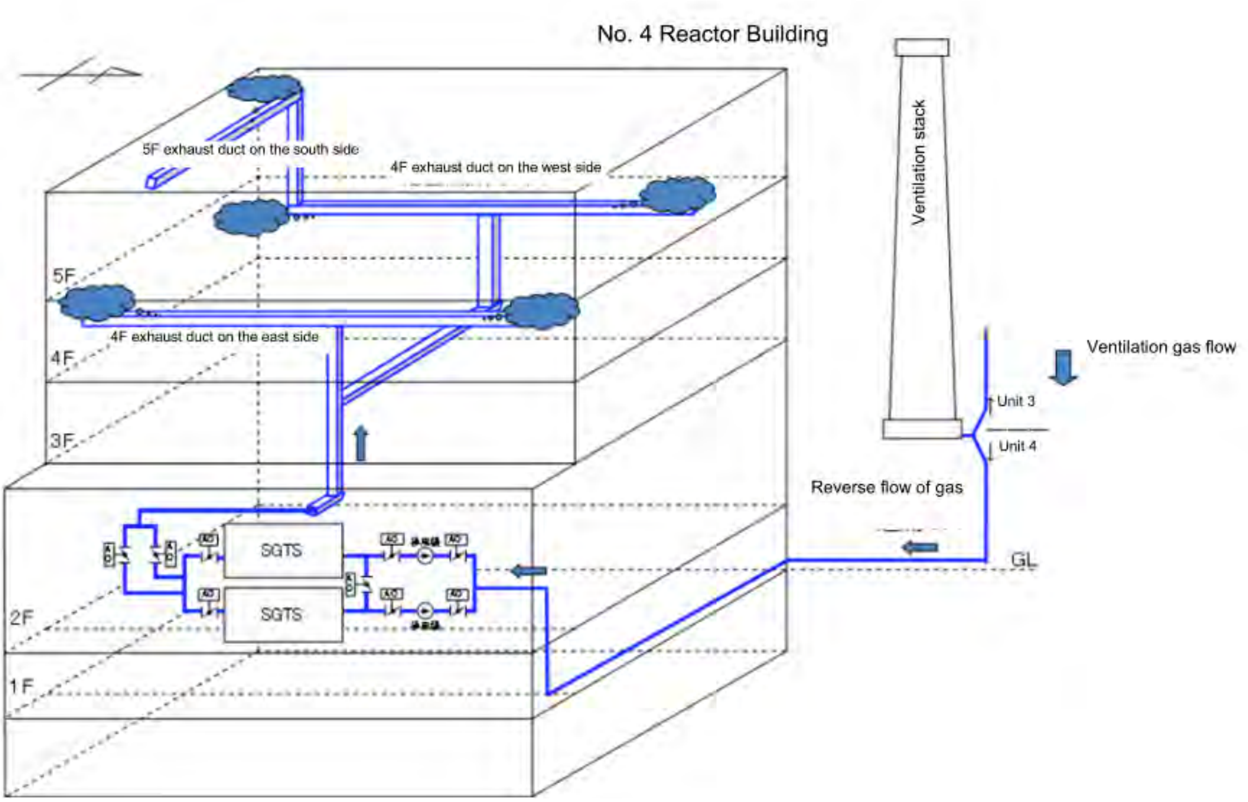


Figure 15:
H_2 overflow from Unit 3 to Unit 4;
source: Ref. 43, Fig. IV 5-10

At present, it is assumed that oil leaks caused the fires in the reactor building on 15.03.2011 at 09:38 and on 16.03.2011 at 05:45 (see Ref. 1 and Ref. 10).

On 21.03.2011 in the time from 06:37 until 08:41, water was for the first time injection by mobile water cannons in order to cool down the spent fuel pool and to compensate the evaporation (see Ref. 3). The water injection was later continued by fire extinguishing pumps and the truck-mounted concrete pump.

Ref. 21 gives evidence of a only a slight debris coverage in the spent fuel pool of Unit 4 due to the hydrogen explosion (see Fig. 16), while no mechanical damage of FA was discernible. A nuclide analysis from 08/09.05.2011 gives evidence of elevated concentration of radionuclides (mainly of Cs-134/137) in the pool as compared to the reference value of 04.03.2011 (see Ref. 38). The question whether these nuclides stem from the FA damage in Unit 4 or if they came from the ingress from the other units cannot be answered conclusively.

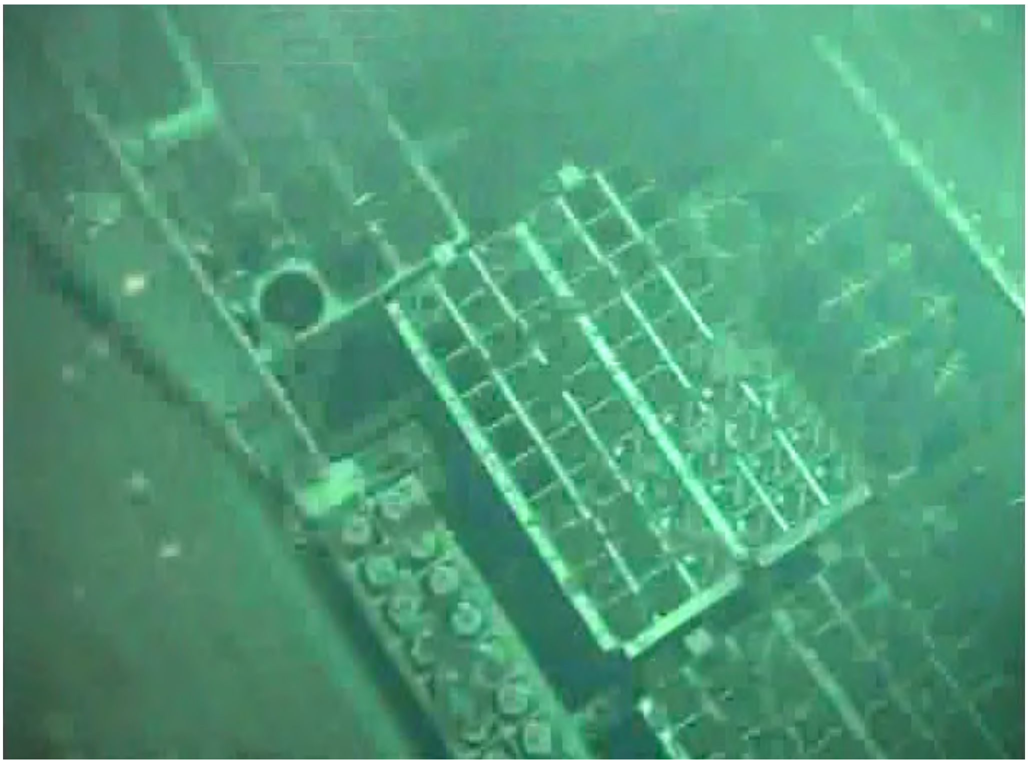


Figure 16:
Spent fuel pool, Unit 4, on 29.04.2011;
source: TEPCO

Annotation 19
The insufficient auxiliary water supply leads to the conclusion that the injection amounts were insufficient. It is unknown whether the appropriate water injection amounts are specified in the Severe Accident Management Guidelines (SAMG) and how they have been verified. Moreover, it is unclear if sufficient material for the necessary accident management was in place at the site. It is also unclear whether the necessary measurement displays (e.g. pool temperature, water level) were available.

1.6 Units 5 and 6

On 11.03.2011 at 15:35, the second tsunami caused the destruction of the cooling water inlet and thus the loss of the ultimate heat sink (mechanical). Moreover, the loss of the emergency DG (by the flooding) caused the loss of the necessary residual-heat removal trains to the ultimate heat sink (sea water cooling) as well as the station blackout (SBO) at 15:38 (see Ref. 43). Units 5 and 6 of the Fukushima Dai-ichi NPP were in outage at the moment of the station blackouts, the RPVs were completely loaded. While Unit 6 was in 'cold shutdown' condition Unit 5 was undergoing RPV leak tests (see Ref. 43).

The third diesel generator (DG) (air-cooled) at Unit 6 was not flooded by the tsunami. As this DG was not impaired by the failure of coolant supply, it remained functional (see Ref. 32).

Due to leak tests (pressure tests) in Unit 5, the pressure in the reactor during SBO amounted to 72 bar; owing to the decay heat, the pressure in the RPV rose for a short time to about 80 bar. On 12.03.2011 at 06:06, pressure relief of the RPV was undertaken. In Unit 6, a rise in RPV pressure was also indicated. The pressure rose more slowly than in Unit 5 due to the low decay heat caused by the long shutdown period (see Ref. 43).

On 14.03.2011 at 05:00, the power supply for the injection from the cold condensate tank was re-established for Unit 5. The pressure relief of both Units was carried out by SRVs, and coolant injection was provided via the cold condensate tank (see Ref. 43).

Caused by diverse tsunami-inflicted failures of equipment, the coolant function of the spent fuel pools was lost. The decay heat brought about a rise in the water temperature and a slow decrease of the water level (see Ref. 1). On 16.03.2011 at about 08:00, according to Ref. 1, the water temperature in both spent fuel pools exceeded 60 °C.

On 19.03.2011, openings were made in the roof of the reactor building to prevent a hydrogen explosion (see Ref. 39).

At first the water injection into the RPV and the spent fuel pool was carried out by the third DG of Unit 6 (air-cooled DG) via cold condensate injections (auxiliary coolant) (see Ref. 3). On 19.03.2011, it became possible to put the second DG of Unit 6 in operation after its repair. The power supply to the residual-heat removal pumps of Unit 5 and Unit 6 could thus be ensured, and the spent fuel pools were cooled again (see Ref. 3).

On 20.03.2011 at 14:30, Unit 5 - and on 20.03.2011 at 19:27, Unit 6, reached the state 'cold shutdown' (see Ref. 3).

On 22.03.2011 at 19:41, all consumers were connected to the off-site power supply (see Ref. 36).

1.7 Common Spent Fuel Pool

Caused by the failure of off-site power supply, a failure of cooling occurred in the so-called 'Common Spent Fuel Pool'. The decay heat from 6375 fuel assemblies (storage capacity 6840 FA – see Ref. 43) brought about a slow rise in the pool temperature (on 11.03.2011 up to about 30°C, see Ref. 43; on 19.03.2011 at 09:00 up to 57°C – see Ref. 3), and the water level decreased. The water injection by fire extinguishing vehicles on 21.03.2011 in the time from 10:37 to 15:30 as well as the re-establishing of the spent fuel pool cooling on 24.03.2011 at 18:05 (see Ref. 3) brought about a continuous decrease in the pool temperature and a stabilisation at < 30 °C.

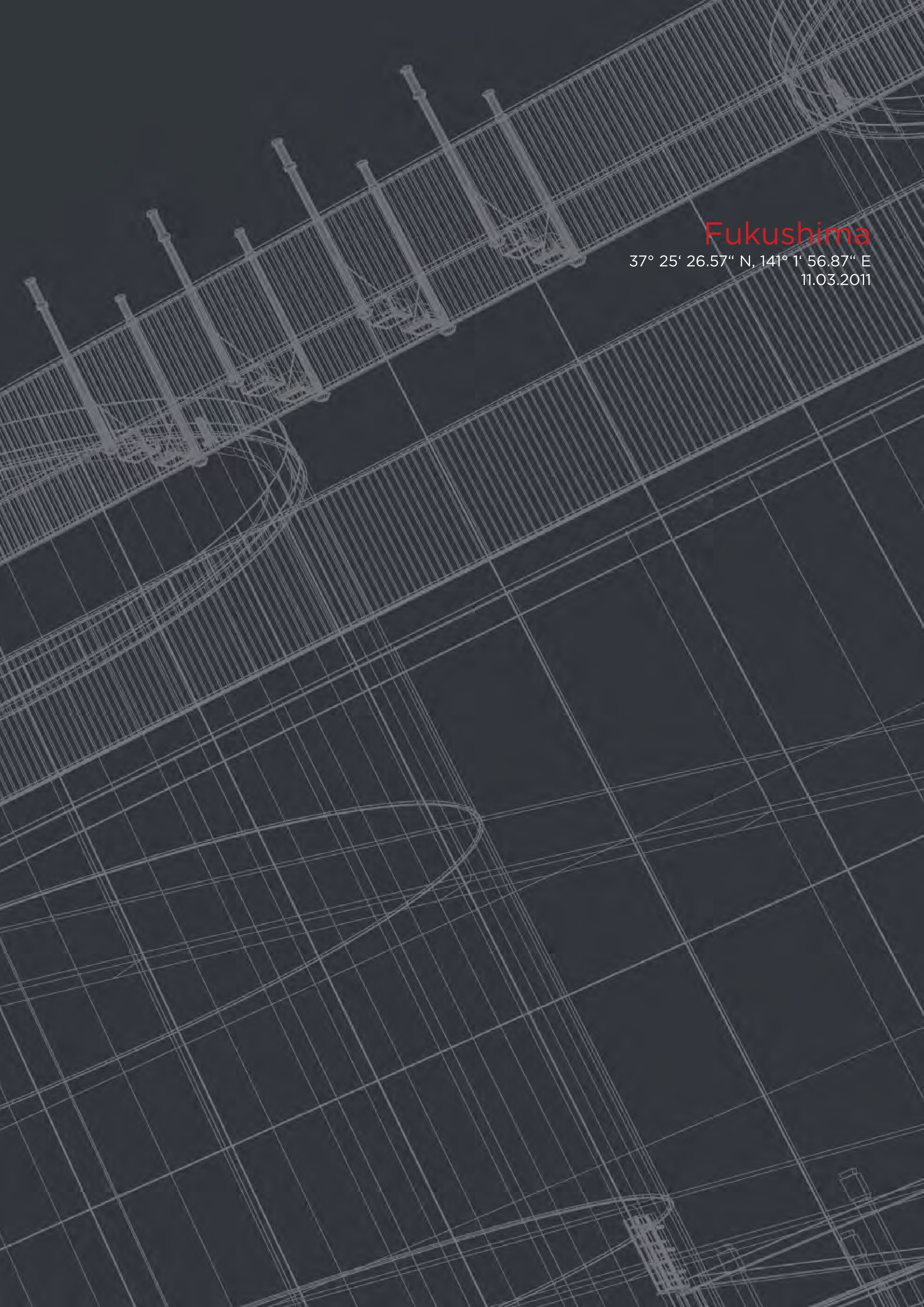
On 13.05.2011, water samples were taken from the Common Spent Fuel Pool to verify the pool integrity. The samples gave evidence of a rise in activity of Cs-134 and Cs-137, as compared to the reference values of February 2011 (see Ref. 22). At present, it is being verified whether the activity rise can be attributed to fuel damage

1.8 Dry Storage Cask Facility

Caused by the station blackout (SBO), a loss of all power systems occurred in the so-called dry storage cask facility. However, the dry storage cask facility has natural convection cooling (see Ref. 11) which ensured that cooling of the FA casks was not impaired.

On 17.03.2011, the operator carried out a visual inspection which did not indicate any deviations from the normal condition (see Ref. 12).

At present it is unclear whether the checks described in Ref. 12 were a detailed inspection, nor is it known what the specific results of a storage and casks inspection were.



Fukushima

37° 25‘ 26.57“ N, 141° 1‘ 56.87“ E
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2 Event Sequence at Fukushima Dai-ni

2.1 The operator of these plants is also TEPCO (Tokyo Electric Power Company).

Before the event, the power units of the Fukushima Dai-ni NPP had been in power operation:

Unit 1
BWR/5, 3293 MW_{th} Mark II,
Manufacturer: Toshiba (1975 – 1982)

Unit 2
BWR/5 advanced, 3293 MW_{th} Mark II,
Manufacturer: Hitachi (1979 – 1984)

Unit 3
BWR/5 advanced, 3293 MW_{th} Mark II,
Manufacturer: Toshiba (1980 – 1985)

Unit 4
BWR/5 advanced, 3293 MW_{th} Mark II,
Manufacturer: Hitachi (1980 – 1987)

on full power operation

The operator of this unit is TEPCO
(Tokyo Electric Power Company).

Figure 17:
Overview Fukushima Dai-ni;
source: TEPCO

Caused by the Tohoku-Chihou-Taiheiyou-Oki earthquake on 11.03.2011 at 14:46 (magnitude 9), automatic reactor SCRAM occurred at Units 1 to 4 (see Ref. 1).

Contrary to Fukushima Dai-ichi, no station black out was caused by the earthquake (see Ref. 14). However, it can be assumed that a short voltage disconnection or voltage peaks occurred, for there were some actuations of the emergency diesel generators, and containment isolation occurred.

The tsunami also caused partial flooding and equipment damage (auxiliary service water of Units 1, 2 and 4) at the Dai-ni site. According to TEPCO (information of 30.3.2011), two emergency DGs of Unit 1 failed irreparably. The DGs of Unit 2 could, despite the flooding, be put back into standby operation on 14.03.2011 after repair and restoration of the cooling function. 2 DGs of Unit 3 and 1 DG of Unit 4 remained operable. The other DGs of Unit 4 could be put back into standby operation on 14.03.2011 after restoration of the cooling function (see Ref. 43).

At this site, the damage turned out to be less severe owing to the siting (located 2 m higher) and the slightly more favourable layout of the buildings. (see Fig. 18).

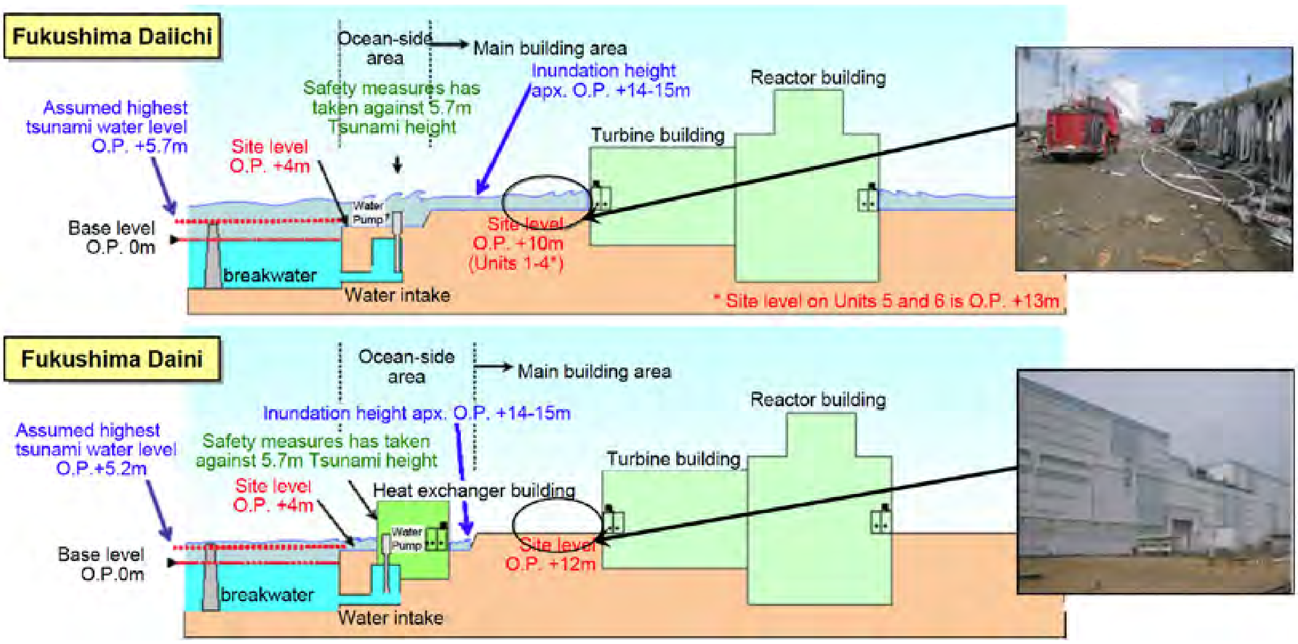


Figure 18:
Flooding as compared between Dai-ichi and Dai-ni;
source: TEPCO

Annotation 20
The question of whether accident management procedures were available for cooling the diesels in the case of a loss of off-site power and how they are specified in the Severe Accident Management Guidelines (SAMG) or how they were verified is unclear. Moreover, it is not completely clear whether sufficient material for the necessary accident management was in place at the site. Presumably, the necessary measurement displays (e.g. pool temperature, water level) were available owing to the off-site power supply.

Annotation 21
A diversified water supply (wells, pools) could have mitigated the accident consequences.

Annotation 22
A reliable physical separation within the coolant pump structures could have protected the nuclear auxiliary service water systems better.

Annotation 23
The reviews which had taken place under the OSART and WANO missions should also have shown up the deficiencies of the plant. Here, no direct reference to the design can be identified in the reviews. However, the design and backfitting of the plant can be indirectly questioned when looking at its 'Operating Experience' (OE) - e.g. during OSART missions by IRS-Reports (e.g. 7342 or 7788) or during WANO missions by the "Significant Operating Experience Reports" (SOER) – describing relevant operating experience of the companies involved. The WANO members have committed themselves to consider specifically the recommendations of WANO–SOER and to review the respective measures in Peer Reviews. This is a voluntary commitment on the part of the operators, while there is no public transparency. As for OSART, the matter is treated differently; here, however, there is no commitment of all countries to implement via the IAEA the necessary and generally accepted measures for safety. Under the periodic safety reviews, the plant safety status has to be re-viewed every decade. Here, there are also different approaches and criteria used within the international framework. Taken together and with the commitment to implement them in a steady process, these three instruments could enhance safety worldwide.

2.2 Unit 1

After the reactor SCRAM, residual-heat removal was carried out as per design by the reactor core isolation cooling system (RCIC). The off-site power supply was in place.

On 11.03.2011 at about 15:38, the tsunami caused a partial destruction of the coolant inlet, hence the loss of the ultimate heat sink (mechanical).

Due to a rise in the pressure of the primary containment, an automatic actuation of the emergency core cooling system (ECCS) occurred. TEPCO assumes that there was a leakage of coolant to the primary containment (see Ref. 13). After the RCIC switched off (12.03.2011 at 03:48), the coolant was supplied from the cold condensate tank.

On 12.03.2011 at 05:22, the pressure suppression function became unavailable due to boiling in the condensate tank (see Ref. 14). The assumption of a coolant leakage to the primary containment could not be confirmed. On 12.03.2011 at 07:10, spraying into the drywell began (see Ref. 43)

On 12.03.2011 at 07:45, after the signal 'loss of pressure relief function', the government ordered the evacuation from the 3 km-zone advised the population in the area of 10 km around Dai-ni to shelter. On 12.03.2011 at 17:39, the evacuation zone was extended to an area of 10 km around Dai-ni (see Ref. 3).

On 12.03.2011 at 08:19, an alert signal indicated that one control rod was not completely inserted. The signal was reversed at 10:43, all control rods were inserted properly (see Ref. 14).

On 12.03.2011 in the time between 09:43 and 18:00, TEPCO prepared pressure relief in the primary containment (see Ref. 14).

On 14.03.2011 at 01:24, after the emergency coolant systems were re-established by re-placement of the actuators of the auxiliary service water pumps, the cool-down of the reactor was resumed. The respective switchgears were damaged irreparably, so the power supply had to be established via temporary cables (see Ref. 43).

On 14.03.2011 at 10:15, the temperature in the torus dropped to below 100 °C (see Ref. 43).

With the auxiliary coolant supply re-established, pressure relief in the primary containment was no longer necessary (see Ref. 17).

On 14.03.2011 at 17:00, the reactor reached 'cold shutdown' condition (see Ref. 15).

On 15.03.2011 in the time between 15:20 and 16:25, a failure of the power supply of the auxiliary service water pump caused a loss of emergency coolant (see Ref. 16).

Annotation 24
As no loss of power occurred and the nuclear auxiliary service water supply could be re-established, no activity was released. Also, it should be asked here how emergency coolant supply procedures are specified in the Severe Accident Management Guidelines (SAMG). Also it is unclear whether sufficient material for emergency procedures was in place at the site.

2.3 Unit 2

After the reactor SCRAM, residual-heat removal was carried out as per design by the reactor core isolation cooling system (RCIC). The off-site power supply was in place.

On 11.03.2011 at about 15:38, the tsunami caused a partial destruction of the coolant inlet, hence the loss of the ultimate heat sink (mechanical).

On 12.03.2011 at 04:50, the RCIC switched off, the coolant supply into the RPV was carried out from the cold condensate tank (see Ref. 14).

On 12.03.2011 at 05:32, the pressure relief function was no longer available due to boiling in the condensate tank (see Ref. 14).

On 12.03.2011 in the time between 10:33 and 22:58, TEPCO prepared pressure relief in the primary containment (see Ref. 14).

On 14.03.2011 at 07:13, after the emergency core cooling system was re-established following the replacement of the actuators of the auxiliary service water pumps, the cool-down of the reactor was resumed. The respective switchgears were damaged irreparably, so the power supply had to be established via temporary cables (see Ref. 43).

On 14.03.2011 at 15:52, the temperature in the torus dropped to below 100 °C (see Ref. 43).

With the auxiliary coolant supply re-established, pressure relief in the primary containment was no longer necessary (see Ref. 17).

On 14.03.2011 at 18:00, the reactor reached ‘cold shutdown’ condition (see Ref. 15).

Annotation 25
As no loss of power occurred and the nuclear auxiliary service water supply could be re-established, no activity was released. Also, it should be asked here how emergency coolant supply procedures are specified in the Severe Accident Management Guidelines (SAMG). Also it is unclear whether sufficient material for emergency procedures was in place at the site.

2.4 Unit 3

After the reactor SCRAM, residual-heat removal was carried out as per design by the reactor core isolation cooling system or the auxiliary service water supply from the cold condensate tank.

On 11.03.2011 at about 15:38, the tsunami caused a partial destruction of the coolant inlet, hence the loss of the ultimate heat sink (mechanical) while train B of the residual-heat removal system (RHR) remained operable (see Ref. 43).

On 12.03.2011 in the time between 12:08 and 12:13, TEPCO prepared preventive pressure relief in the primary containment (see Ref. 14).

On 12.03.2011 at 12:15, the reactor reached 'cold shutdown' condition (see Ref. 14).

2.5 Unit 4

After the reactor SCRAM, residual-heat removal was carried out as per design by the reactor core isolation cooling system (RCIC). The off-site power supply was in place.

On 11.03.2011 at about 15:38, the tsunami caused a partial destruction of the coolant inlet, hence the loss of the ultimate heat sink (mechanical).

On 12.03.2011 (exact time unknown), the RCIC switched off, the coolant supply into the RPV was carried out from the cold condensate tank (see Ref. 14).

On 12.03.2011 at 06:07, the pressure relief function was no longer available due to boiling of the condensate tank (see Ref. 14). On 12.03.2011 at 07:35, spraying in the drywell began (see Ref. 43).

On 12.03.2011 in the time between 11:44 and 11:52, TEPCO prepared pressure relief in the primary containment (see Ref. 14).

On 12.03.2011 at 12:43, there was an alert signal indicating that one control rod was not completely inserted. The signal was reversed by another signal; all control rods inserted properly (see Ref. 23).

On 14.03.2011 at 15:42, after the emergency core cooling system was re-established following the replacement of the actuators o the auxiliary service water pumps, the cool-down of the reactor was resumed. The respective switchgears were damaged irreparably, so the power supply had to be established via temporary cables (see Ref. 43). With the auxiliary service water supply re-established, pressure relief of the primary containment was no longer carried out (see Ref. 16).

On 15.03.2011 at 07:15, the reactor reached 'cold shutdown' condition (see Ref. 43).

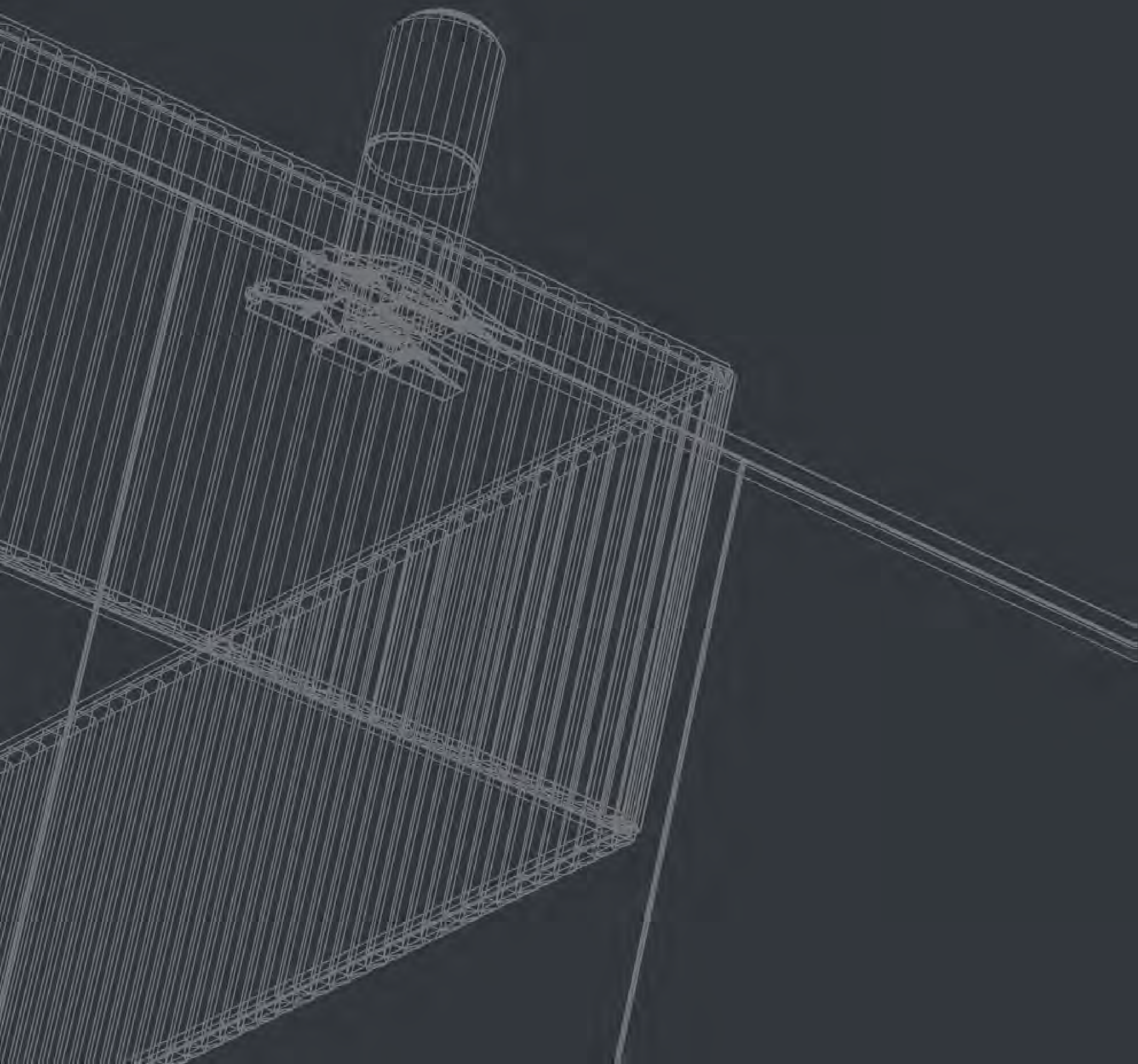
Annotation 26
As no loss of power occurred and the nuclear auxiliary service water supply could be re-established, no activity was released. Also, it should be asked here how emergency coolant supply procedures are specified in the Severe Accident Management Guidelines (SAMG). Also it is unclear whether sufficient material for emergency procedures was in place at the site.

On 15.03.2011 in the time between 20:05 and 21:25, there was an interruption in the supply of emergency coolant due to a failure in the power supply of the auxiliary service water pump (see Ref. 16).

Fukushima

37° 25‘ 26.57“ N, 141° 1‘ 56.87“ E

11.03.2011



3 Abbreviations

AC	Alternate Current
BAF	Bottom of Active Fuel
FA	Fuel Assembly
BWR	Boiling Water Reactor
CCF	Common Cause Failure
DC	Direct Current
DG	Diesel Generator
DW	Drywell
ECCS	Emergency Core Cooling System
GE	General Electric Company
HPCI	High Pressure Coolant Injection
IAEA	International Atomic Energy Agency
IC	Isolation Condenser
IRS	Incident Reporting System
JAIF	Japan Atomic Industrial Forum Inc.
JMA	Japan Meteorological Agency
JST	Japan Standard Time
LOCA	Loss of Coolant Accident
LL	Low Low – Actuation Value
LOOP	Loss of Off-Site Power
METI	Ministry of Economy, Trade and Industry
NISA	Nuclear and Industrial Safety Agency
ADR	Ambient Dose Rate
OE	Operating Experience
OSART	Operational Safety Team
RCIC	Reactor Core Isolation Cooling
RPV	Reactor Pressure Vessel
RHR	Residual Heat Removal
SAMG	Severe Accident Management Guidelines

SCRAM	Safety Control Rod Axe Man
SOER	Significant Operating Experience Reports
SRV	Safety Relief Valve
SBO	Station Blackout
TAF	Top of Active Fuel
TEPCO	Tokyo Electric Power Company
USNRC	United States Nuclear Regulatory Commission
VGB	Verband der Grosskessel-Besitzer
WANO	World Association of Nuclear Operators

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