APPENDIX F: THE FUKUSHIMA DAIICHI ACCIDENT

At 2.46pm Japan Standard Time (JST) on Friday 11 March 2011, a magnitude 9.0 earthquake struck 130 km off the north-east coast of Japan's main island of Honshu. The Great East Japan earthquake was caused by 'a sudden release of energy at the interface where the Pacific tectonic plate forces its way under the North American tectonic plate'.[1] The earthquake lasted for more than two minutes and caused significant damage to infrastructure and property along the east coast of Japan.[2] It also resulted in a 10–20 m horizontal shift of the sea floor and local coastal subsidence of about half a metre.[3]

When the earthquake struck, three of the six reactor units at Tokyo Electric Power Company's (TEPCO) Fukushima Daiichi nuclear power plant were operating at full power. Units 1–3 shut down automatically according to design when plant sensors detected ground vibrations and triggered the reactor protection systems, thereby controlling the reactivity of the nuclear fuel, which is a fundamental safety function.[4] Units 4–6 were in planned shutdown for maintenance and refuelling at the time.[5] Although the earthquake caused no significant damage to the reactor units, it did cut off external AC power supply to the plant.[6] Emergency cooling was maintained as per design by diesel generators located in the basements of the turbine buildings of each reactor unit.[7]

The earthquake caused two tsunamis. Several warnings were issued by the government.[8] The first small tsunami was measured by a wave height meter located 1.5 km off the coast of the Fukushima Daiichi plant at 3.27pm JST.[9] The main tsunami, measuring 14–15 m in run-up height[10], struck the Fukushima Daiichi site at 3.36–3.37pm JST, and ultimately flooded over 500 square kilometres of land.[11] More than 15 000 people were killed and over 6000 injured as a result of the earthquake and tsunami, and around 2500 people were reported to still be missing as of March 2015.[12]

THE IMPACTS OF THE TSUNAMI ON FUKUSHIMA DAIICHI

Units 1–4 of the Fukushima Daiichi plant were built 10 m above sea level, while Units 5 and 6 had elevations of 13 m (see Figure F.1 and Figure F.2).[13] A 4-metre-high sea wall, with a breakwater height of 5.5 m, had been constructed to shield the plant from potential tsunami waves.[14] The sea wall and breakwater protected the site against the small wave, which had a run-up height of 4–5 m.[15] However, the main tsunami wave inundated the Fukushima Daiichi site, flooding and disabling 12 of the plant's 13 emergency diesel AC power generators, located at an elevation of 2 m.[16] This affected the cooling systems of the reactors and spent fuel pools.[17] In addition to disabling the emergency generators, the tsunami flooded the 125 volt DC batteries that supplied power to the instruments for Units 1, 2 and 4, which resulted in the loss of the instruments, controls and lighting for these units.[18]

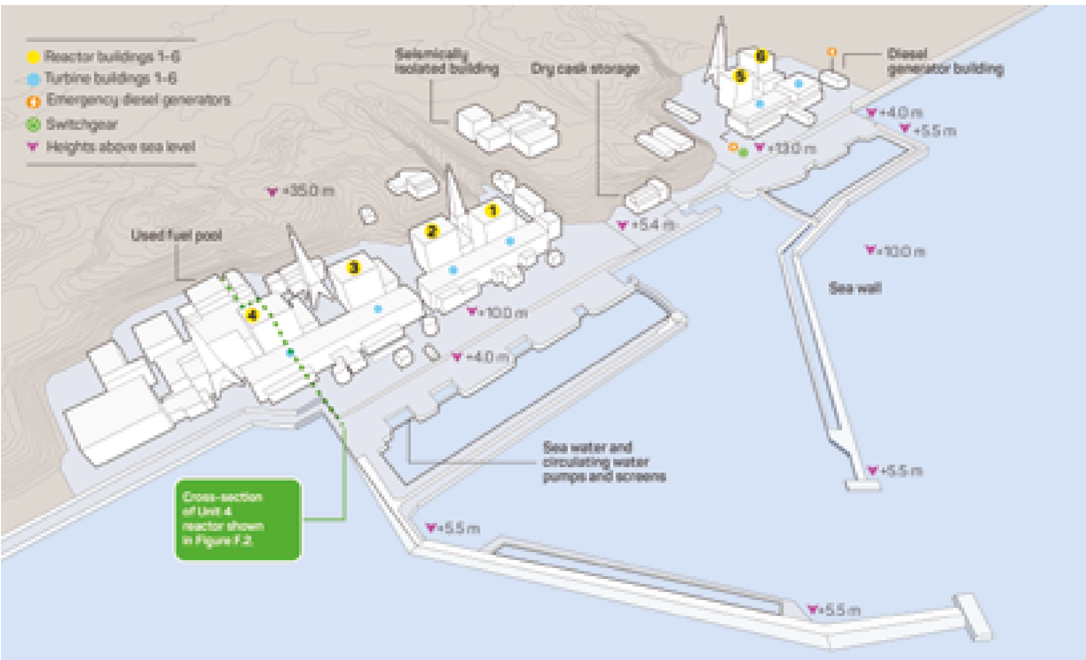

Figure F:1: The elevations and locations of structures and components at the Fukushima Daiichi nuclear power plant

Image adapted from TEPCO data

The widespread destruction caused by the tsunami made it impossible for external electricity supplies to be restored in time to avert melting of the fuel.

Without cooling and water injection, the heat generated by radioactive decay in the fuel caused the water levels in Units 1–3 to drop.[19] The loss of cooling for an extended period of time meant that the nuclear fuel overheated. The high temperatures also caused the exposed zirconium fuel cladding to react with the water vapour in the units resulting in the formation of large quantities of hydrogen gas.[20]

The hydrogen gas leaked from the primary containment vessels, resulting in explosions inside the reactor buildings of Units 1, 3 and 4. In addition, for Units 1, 2 and 3, the extended periods without cooling led to core melting and subsequent damage to the floors of the reactor vessels.[21] Hydrogen gas in Units 1 and 3 migrated from the primary containment vessels and caused explosions on the service floors, which injured workers and damaged the reactor buildings (see Figure F.3).[22] An explosion in the Unit 4 reactor building was caused by the migration of hydrogen gas produced in Unit 3 via a common ventilation system.[23] This destroyed the structure above the service floor and also injured workers.[24] It is thought that there was a containment vessel failure and uncontrolled releases of radioactive materials from Unit 2, though this has not yet been confirmed.[25]

Approximately nine days after the initial loss of power to the plant, AC power was restored to Units 1 and 2.[26] Units 3 and 4 were connected to off-site power approximately one week after Units 1 and 2.[27] Power was restored to Unit 5 through a power line connection to the diesel generators located at Unit 6.[28] On 20 March 2011, Units 5 and 6 were the first to reach a 'cold shutdown state' after the reactor temperatures were brought below 100 °C.[29]

During their response to the nuclear accident, emergency workers attempted to control the escalation of events to limit their impacts. They focused on maintaining cooling in the reactors using the reactor cooling systems[30], but also improvised methods, such as using fire engines to directly inject cooling water into the reactors, and attempted to re-establish temporary AC power.[31] Where damage from the tsunami or hydrogen explosions made this impossible[32], operators tried to prevent or limit the release of radioactive material from the reactor units. Activities included manual venting to depressurise the reactor or containment vessels.[33]

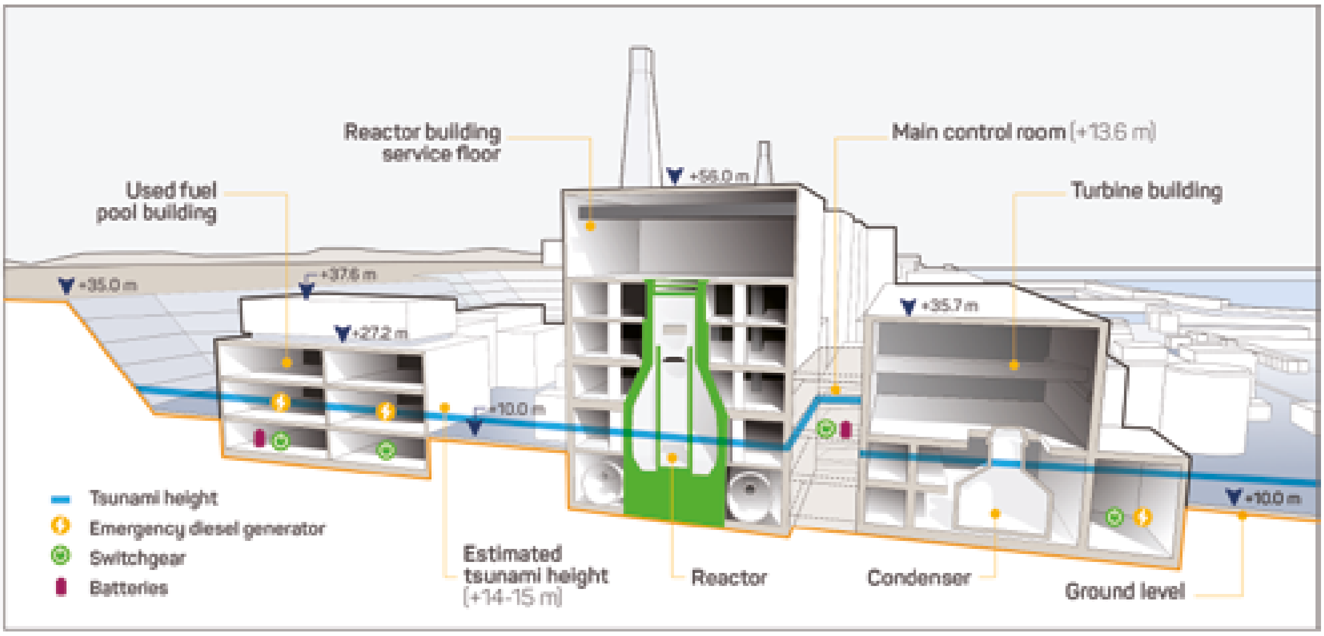

Figure F.2: Cross-section of Unit 4 showing elevations of the plant and the equipment, and the tsunami height

Image adapted from TEPCO data

Figure F.3: Fukushima Daiichi Unit 3 as it appeared on 15 March 2011

Image courtesy of TEPCO

In response to the accident and the potential radiological hazard posed to the surrounding population, the Fukushima Prefecture and, subsequently, the Japanese Government made successive evacuation declarations of increasing radius from the evening of 11 March to 12 March. The Japanese Government also ordered residents within a 20–30 km radial zone to shelter until 25 March.[34] On 16 December 2011, the Japanese Government and TEPCO announced the close of the 'accident phase' of the events at the Fukushima Daiichi plant (see Figure F.4).[35]

There have been no deaths or cases of radiation sickness (of workers, emergency responders and members of the public) attributable to the nuclear accident.[36] However, three workers at the Fukushima Daiichi plant were killed by the earthquake and tsunami.[37] The psychological stress experienced by evacuees as a consequence of the accident and tsunami and the dislocation of evacuees from their communities and livelihoods has had significant health and social impacts.[38]

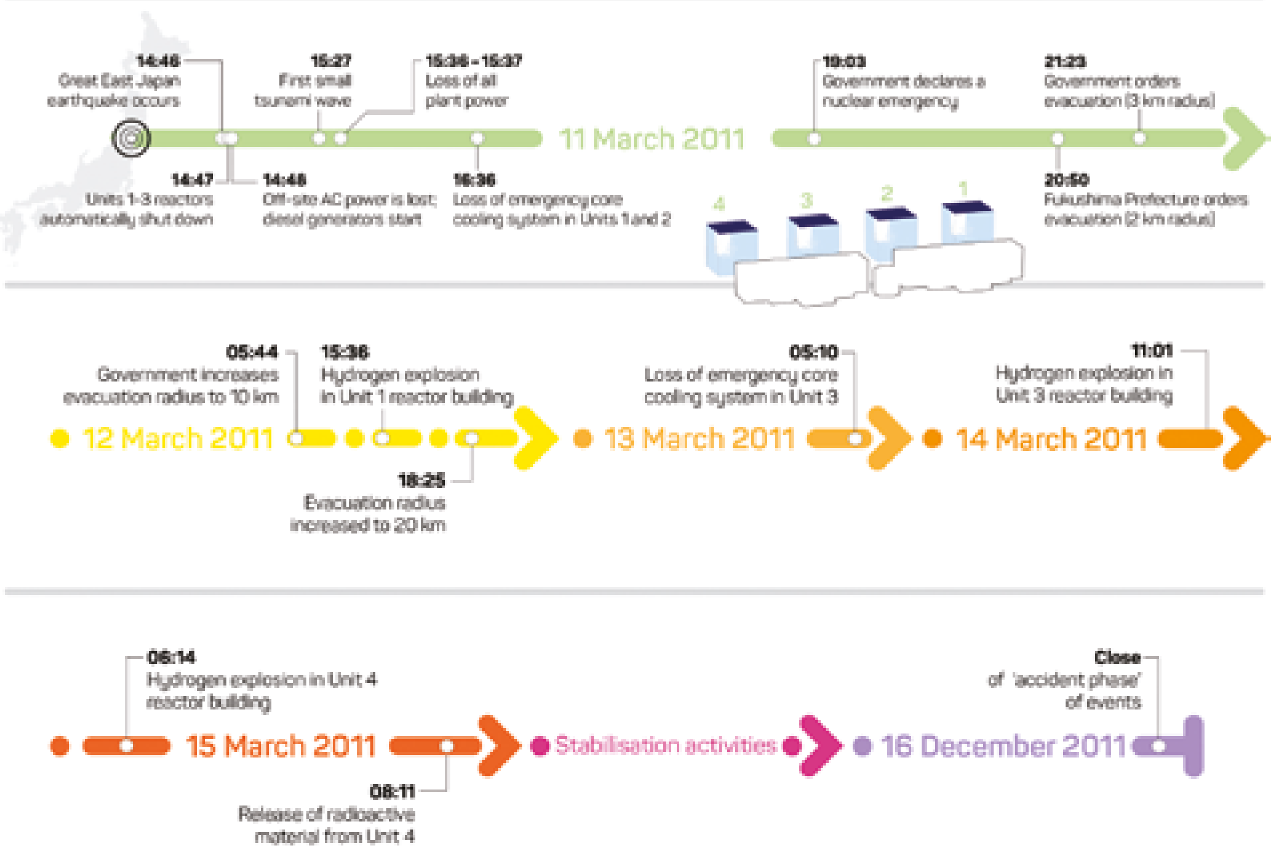

Figure F.4: Timeline of events for 11–15 March 2011, and up to 16 December 2011

Fukushima is an agricultural prefecture, and the economic impacts of the nuclear accident on agricultural production and food consumption, given the radioactive contamination, have been significant. There has also been a wider economic impact in Japan as a consequence of the nuclear accident, as forced reactor shutdowns resulted in a rise in energy imports at significant cost.[39]

The broader impacts of the earthquake and tsunami included damage to or destruction of at least 332 395 buildings, 2126 roads, 56 bridges and 26 railways along the east coast of Honshu. Electricity, gas and water supplies, telecommunications and railway services were also disrupted.[40] The estimated total loss for the Japanese economy caused by the earthquake and tsunami is in the order of US$309 billion.[41]

CAUSES OF THE ACCIDENT

There were a number of deficiencies in the plant design, emergency preparedness, regulatory framework and safety culture in Japan that contributed to the accident and the severity of its impacts.

The Fukushima Daiichi plant was only designed to withstand earthquakes up to magnitude 8.0 and tsunamis up to 5.5 m in height. This design was based on historical seismic records and was not updated to reflect new learning or studies of more recent seismic and tsunami events, nor the experiences of other countries that had faced emergencies at nuclear power plants.[42] Given the magnitude 9.0 earthquake and the 14–15 m tsunami, the events went 'beyond design basis'.[43]

The consequence of the earthquake and tsunami was the simultaneous loss of power to multiple reactor units for an extended period. This revealed several unchallenged design assumptions that:

- nuclear technologies and, particularly, the Fukushima Daiichi plant, were so safe that an accident of the kind experienced was thought to be impossible[44]
- there would never be a loss of power to all units at the same time and any power outage would only be for a short time[45]
- there would not be more than one event to which operators would simultaneously have to respond.[46]

In addition to the design flaws and unchallenged assumptions, workers lacked appropriate training for emergency management, and emergency operational guidelines were inadequate at both the regulatory and corporate levels.[47]

Owing to the nature of the emergency, workers were required to improvise solutions, often without appropriate equipment.[48]

Japan's regulatory framework for nuclear power plants was deficient at the time of the accident.[49] The framework was complex, with a number of agencies having overlapping responsibilities.[50] Additionally, regulators were not sufficiently independent of nuclear power companies[51], including TEPCO.[52] The safety culture at the Fukushima Daiichi plant was characterised by complacency, in which operators and stakeholders did not challenge the assumptions.[53] Accordingly, there was no innovation in the safety culture or the regulatory framework.[54]

Tsunami countermeasures plus normal and emergency operating procedures were not aligned with International Atomic Energy Agency (IAEA) guidelines, and periodic safety inspections did not comply with international standards.[55] Despite this, Japan's Nuclear and Industrial Safety Agency permitted the Fukushima Daiichi plant to operate, and did not require improvements to safety and design, including implementing countermeasures for extreme natural events and emergency preparedness.[56]

As reported in Chapter 4, Electricity generation, a number of lessons learned from the Fukushima Daiichi nuclear accident are being applied to existing nuclear power plants and new nuclear developments. The report by the Director General of the IAEA identifies 45 lessons to improve nuclear safety and emergency preparedness in the wake of the Fukushima Daiichi nuclear accident.[57] Other lessons have been reported by TEPCO[58], the United States National Academy of Sciences[59], the United States Nuclear Regulatory Commission[60], the Institute of Nuclear Power Operations[61], and Greenpeace International.[62]

THE STATUS OF DECOMMISSIONING AND REMEDIATION WORKS

Since the Fukushima Daiichi accident, TEPCO and relevant Japanese Government agencies have developed a plan to decommission Units 1–4 and a strategy to remediate the site and surrounding environment.[63] The first phase of the decommissioning plan—removal of fuel from the spent fuel pools—is ongoing.[64] The second phase—removal of fuel debris from the site—is expected to take ten years.[65] Full decommissioning of Units 1–4 is expected to take 30 to 40 years.[66] The remediation strategy aims to reduce the radiation exposure from contaminated land areas by taking direct action on the contaminated areas and limiting exposure pathways to humans.[67] The costs of decommissioning have been estimated at ¥976 billion (A$10.74 billion), while compensation costs are estimated to be ¥6441.2 billion (A$70.88 billion). Combined, the costs amount to approximately ¥7417.2 billion (A$81.62 billion).[68] The true costs will only become known once decommissioning works are complete.

According to one estimate, approximately 135 000 people remain evacuated.[69] This figure includes 75 000 residents evacuated due to the nuclear accident and a further 60 000 evacuated due to the tsunami and earthquake.[70] Some evacuees have now been able to return to their homes.[71] Consistent with the international nuclear liability system, compensation is being paid to evacuees, homeowners and businesses for pain and suffering, loss of property, expenses incurred from evacuation and loss of income or revenue.[72] In September 2011, the Japanese Government established the Nuclear Damage Compensation Facilitation Corporation (renamed the Nuclear Damage Compensation and Decommissioning Facilitation Corporation in August 2014) to oversee decommissioning and remediation works and the compensation scheme.[73]

A significant amount of contaminated water has accumulated on the Fukushima Daiichi site.[74] This water is treated to remove all radionuclides except for tritium, which restricts the ability to release treated water to the sea. Accordingly, the treated water is stored on the site in tanks.[75] Some contaminated water has been released to the sea due to equipment failure and heavy rainfall. More extensive monitoring and mitigation measures have been introduced, but a sustainable solution is yet to be developed.[76]

Research into demonstration-scale technology to remove tritium with a view to full-scale operation is ongoing.[77]

NOTES

1 International Atomic Energy Agency (IAEA), *The Fukushima Daiichi accident: Report by the Director General*, GC(59)/14, IAEA, Vienna, 2015, p. 23.

2 IAEA, *The Fukushima Daiichi accident*, pp. 1, 23.

3 World Nuclear Association (WNA), 'Fukushima accident', March 2016, http://www.world-nuclear.org/information-library/safety-and-security/safety-of-plants/fukushima-accident.aspx

4 The safety systems for controlling the reactivity of nuclear fuel in the reactor core are the reactor protection and control rod drive systems. Before the earthquake, Fukushima Daiichi Units 1–3 were operating, while Units 4–6 were shut down for maintenance and refuelling. The reactors in Units 1–3 were automatically shut down by their reactor protection systems, which were activated by the plant's seismic event monitoring equipment. The insertion of control rods by the control rod drive systems stopped the nuclear chain reaction in the nuclear fuel and shutdown the reactors. IAEA, *The Fukushima Daiichi accident*, pp. 5, 24.

5 Eleven reactors at four nuclear power plants were operating in the region when the earthquake occurred and were shut down automatically. In addition to Fukushima Daiichi Units 1–3, TEPCO's Fukushima Daini Units 1–4, Tohoku's Onagawa Units 1–3, and Japco's Tokai reactor were operating. WNA, 'Fukushima accident'; IAEA, *The Fukushima Daiichi accident*, p. 1.

6 WNA, 'Fukushima accident'.

7 IAEA, *The Fukushima Daiichi accident*, p. 24.

8 The first tsunami warning was issued three minutes after the earthquake (2.49pm) and predicted a 3 m wave height. The second tsunami warning was issued at 3.15pm, 29 minutes after the earthquake, and predicted a 6 m wave. A third warning was issued at 3.30pm, 44 minutes after the earthquake, and predicted a wave height greater than 10 m. Committee on Lessons Learned from the Fukushima Nuclear Accident for Improving Safety and Security of U.S. Nuclear Plants, Nuclear and Radiation Studies Board, Division on Earth and Life Studies; National Research Council (Committee on Lessons Learned), *Lessons learned from the Fukushima nuclear accident for improving safety and security of U.S. nuclear plants*, National Academy of Sciences, The National Academies Press (NAP), Washington, D.C., 2014, p. 103.

9 Committee on Lessons Learned, *Lessons learned*, pp. 90–91.

10 Higher run-up (maximum 39 m) and inundation (maximum 33 m) heights were experienced at other locations along the Japanese coast. IAEA, *The Fukushima Daiichi Accident*, p. 30.

11 United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), *Sources, effects and risks of ionizing radiation*, UNSCEAR 2013 Report to the General Assembly with scientific annexes, vol. 1, Scientific Annex A: Levels and effects of radiation exposure due to the nuclear accident after the 2011 great east-Japan earthquake and tsunami, UNSCEAR, UN, New York, 2014, p. 6.

12 IAEA, *The Fukushima Daiichi accident*, p. 1.

13 Elevations are relative to the Onahama Peil (Onahama Port Construction Standard Surface) (OP). Elevations have not been corrected for the ground subsidence that occurred as a result of the earthquake. Committee on Lessons Learned, *Lessons learned*, p. 84.

14 Committee on Lessons Learned, *Lessons learned*, p. 84.

15 IAEA, *The Fukushima Daiichi accident*, pp. 30–31.

16 Committee on Lessons Learned, *Lessons learned*, p. 84.

17 Tokyo Electric Power Company (TEPCO), *The development of lessons from the Fukushima Daiichi nuclear accident*, TEPCO, March 2013, p. 12.

18 IAEA, *The Fukushima Daiichi accident*, p. 32.

19 ibid., pp. 35, 42–43.

20 ibid., p. 57.

21 ibid.

22 ibid., p. 38.

23 ibid., p. 58.

24 ibid., p. 42.

25 ibid., p. 43.

Transcripts and submissions can be found at the Nuclear Fuel Cycle Royal Commission's website: www.nuclearrc.sa.gov.au/transcripts and www.nuclearrc.sa.gov.au/submissions

26 ibid., pp. 44–47.

27 ibid., p. 47.

28 ibid.

29 The term 'cold shutdown state' was defined by the Japanese Government specifically for the Fukushima Daiichi reactors. Its definition differs from the terminology used by the IAEA. IAEA, *The Fukushima Daiichi accident*, pp. 47–48.

30 IAEA, *The Fukushima Daiichi accident*, p. 26.

31 ibid., pp. 34–44.

32 ibid., pp. 37, 39, 42.

33 ibid., pp. 35–43.

34 ibid., p. 84.

35 ibid., p. 48.

36 UNSCEAR, *Sources, effects and risks*, p. 10.

37 WNA, 'Fukushima accident'.

38 Transcript: Weightman, p. 831. UNSCEAR, *Sources, effects and risks*, pp. 77, 80.

39 Transcript: Weightman, p. 831. V Vivoda & G Graetz, 'Nuclear policy and regulation in Japan after Fukushima: Navigating the crisis', *Journal of Contemporary Asia* 45, no. 3, p. 493.

40 United States Geological Survey (USGS), Earthquake summary, 23 March 2015, http://earthquake.usgs.gov/earthquakes/eqinthenews/2011/usc0001xgp/#summary

41 USGS, Earthquake summary.

42 Earthquakes in Chile in 1960 and 2010 registered magnitudes of 9.5 and 8.8 respectively, while earthquakes in Alaska (1964) and Sumatra (2004) recorded magnitudes of 9.2; IAEA, *The Fukushima Daiichi accident*, pp. 3–4, 23.

43 Transcript: Caruso, p. 821.

44 Transcript: Caruso, p. 825. IAEA, *The Fukushima Daiichi accident*, foreword.

45 IAEA, *The Fukushima Daiichi accident*, pp. 6, 59.

46 ibid., p. 5.

47 ibid., pp. 4, 59.

48 Transcript: Caruso, p. 822; IAEA, *The Fukushima Daiichi accident*, foreword.

49 Transcript: Weightman, p. 833.

50 ibid., p. 837.

51 ibid., p. 839.

52 Transcript: Caruso, p. 824. Vivoda & Graetz, 'Nuclear policy and regulation', pp. 497–500.

53 Transcript: Caruso, p. 824. IAEA, *The Fukushima Daiichi accident*, Foreword. p. 68.

54 Transcript: Caruso, p. 826.

55 Transcript: Weightman, p. 832.

56 WNA, 'Fukushima accident'.

57 IAEA, *The Fukushima Daiichi accident*.

58 TEPCO, *The development of lessons*.

59 Committee on Lessons Learned, *Lessons learned*.

60 United States Nuclear Regulatory Commission (U.S.NRC), *What are the lessons learned from Fukushima?* U.S.NRC, 17 April 2015, http://www.nrc.gov/reactors/operating/ops-experience/japan-dashboard/priorities.html

61 Institute of Nuclear Power Operations (INPO), *Lessons learned from the nuclear accident at the Fukushima Daiichi nuclear power station*, INPO 11-005, INPO, August 2012.

62 Greenpeace International, *Lessons from Fukushima*, Greenpeace International, Amsterdam, February 2012.

63 IAEA, *The Fukushima Daiichi accident*, pp. 15–16.

64 WNA, 'Fukushima accident'.

65 TEPCO, *The development of lessons*, p. 37.

66 IAEA, *The Fukushima Daiichi accident*, p. 17.

67 ibid., p. 15.

68 T Holloway (Australian Embassy), letter to Nuclear Fuel Cycle Royal Commission on Fukushima Daiichi NPP accident costs, 25 April 2016. Currencies have been converted based on the average 2015 conversion rate – ¥1 = A$0.011.

69 WNA, 'Fukushima accident'.

70 ibid.

71 WNA, 'Fukushima accident'; IAEA, *The Fukushima Daiichi accident*, Foreword.

72 S Matsuura, 'The current progress of relief of victims of nuclear damage caused by the Fukushima Daiichi nuclear power plant accident', in Organisation of Economic Co-operation and Development (OECD) – Nuclear Energy Agency (NEA), *Japan's compensation system for nuclear damage: as related to the TEPCO Fukushima Daiichi nuclear accident*, OECD–NEA, 2012, p. 34.

73 The Nuclear Damage Compensation and Decommissioning Facilitation Corporation (NDF), *The Nuclear Damage Compensation and Decommissioning Facilitation Corporation*, February 2016, p. 1.

74 IAEA, *The Fukushima Daiichi accident*, p. 149.

75 ibid.

76 ibid., p. 150–151.

77 World Nuclear News, 'Russia completes design papers for Fukushima tritium removal', 9 July 2015, http://www.world-nuclear-news.org/RS-Russia-completes-design-papers-for-tritium-removal-at-Fukushima-09071501.html

Transcripts and submissions can be found at the Nuclear Fuel Cycle Royal Commission's website: www.nuclearrc.sa.gov.au/transcripts and www.nuclearrc.sa.gov.au/submissions