# Nuclear Power Plants and Earthquakes

(*August 2009*)

- **Japanese, and most other, nuclear plants are designed to withstand earthquakes, and in the event of major earth movement, to shut down safely.**
- **In 1995, the closest nuclear power plants, some 110 km north of Kobe, were unaffected by the severe Kobe-Osaka earthquake, but in 2004, 2005, 2007 and 2009 Japanese reactors shut down automatically due to ground acceleration exceeding their trip settings.**
- **In 1999, three nuclear reactors shut down automatically during the devastating Taiwan earthquake, and were restarted two days later.**

## Design criteria

Nuclear facilities are designed so that earthquakes and other external events will not jeopardise the safety of the plant. In France for instance, nuclear plants are designed to withstand an earthquake twice as strong as the 1000-year event calculated for each site. It is estimated that, worldwide, 20% of nuclear reactors are operating in areas of significant seismic activity.

Because of the frequency and magnitude of earthquakes in Japan, particular attention is paid to seismic issues in the siting, design and construction of nuclear power plants. The seismic design of such plants is based on criteria far more stringent than those applying to non-nuclear facilities. Power reactors are also built on hard rock foundations (not sediments) to minimise seismic shaking.

Japanese nuclear power plants are designed to withstand specified earthquake intensities evident in ground motion. These used to be specified as S1 and S2, but now simply Ss, in Gal units. The plants are fitted with seismic detectors. If these register ground motions of a set level (formerly 90% of S1), systems will be activated to automatically bring the plant to an immediate safe shutdown. The logarithmic Richter magnitude scale (or more precisely the Moment Magnitude Scale more generally used today) measures the overall energy released in an earthquake, and there is not always a good correlation between that and intensity (ground motion) in a particular place. Japan has a seismic intensity scale in shindo units 1 to 7.

The revised seismic regulations released in May 2007 increased the Ss figure to be equivalent to 6.7 on the Richter or Moment Magnitude scale - a factor of 1.5 (up from a magnitude of 6.5). PGA is measured in Galileo units - Gal ($cm/sec^2$) or g - the force of gravity, one g being 980 Gal.

The design basis earthquake ground motion or peak ground acceleration (PGA) S1 was defined as the largest earthquake which can reasonably be expected to occur at the site of a nuclear power plant, based on the known seismicity of the area and local active faults. A power reactor could continue to operate safely during an S1 level earthquake, though in practice they are set to trip at lower levels. If it did shut down, a reactor would be expected to restart soon after an S1 event. The revised seismic regulations released in May 2007 increased the S1 figure to be equivalent to 6.7 on the logarithmic Richter scale - a factor of 1.5 (up from 6.5). PGA is measured in Galileo units - Gal (cm/sec2) or g - the force of gravity, one g being 980 Gal. The non-SI unit is used here.

Larger earthquake ground motions (PGAs) in the region, considering the tectonic structures and other factors, must also be taken into account, although their probability is very low. The largest conceivable such ground motion was the upper limit design basis extreme earthquake ground motion (PGA) S2, generally assuming a magnitude 6.5 earhtquake directly under the reactor. The plant's safety systems would be effective during an S2 level earthquake to ensure safe shutdown without release of radioactivity, though extensive inspection would be required before restart. In particular, reactor pressure vessel, control rods and drive system and reactor containment should suffer no damage at all.

After the magnitude 7.2 Kobe earthquake in 1995 a panel was set up to review the safety of

nuclear facilities in Japan and the design guidelines for their construction. The Japanese Nuclear Safety Commission (NSC) then approved the panel's report. Building and road construction standards were also thoroughly reviewed at this time. After recalculating the seismic design criteria required for a nuclear power plant to survive near the epicentre of a large earthquake the NSC concluded that under current guidelines such a plant could survive a quake of magnitude 7.75. The Kobe earthquake was 7.2.

Japan's Rokkasho reprocessing plant and associated facilities are built on stable rock and are designed to withstand an earthquake of magnitude 8.25.

Following a magnitude 7.3 earthquake in 2000 in an area where no geological fault was known, Japan's NSC ordered a full review of the country's 1978 seismic guidelines (which had been adopted by the NSC in 1981 and partially revised in 2001). This reported in 2006 and resulted in NSC and the Nuclear & Industrial Safety Agency (NISA) calling for reactor owners with NISA to undertake plant-specific reviews of seismic safety, to be completed in 2008. The main result of this review was that the S1 – S2 system was formally replaced by NSC in September 2006 with a single Design Basis Earthquake Ground Motion (DBGM Ss). The main reactor facilities "shall maintain their safety functions under the seismic force caused by DBGM Ss." They and ancillary facilities should also withstand the "seismic force loading of those caused by Elastically Dynamic Design Earthquake Ground Motion Sd (EDGM Sd)" calculated from stress analysis and being at least half the Ss figure.

In March 2008 Tepco upgraded its estimates of likely PGA for Fukushima to 600 Gal, and other operators have adopted the same figure. In October 2008 Tepco accepted 1000 Gal (1.02g) PGA as the new Ss design basis for Kashiwazaki Kariwa, following the July 2007 earthquake there.

Japanese nuclear plants such as Hamaoka near Tokai are in regions where earthquakes of up to magnitude 8.5 may be expected. In fact the Tokai region has been racked by very major earthquakes about every 150 years, and it is 155 years since the last big one. Chubu's Hamaoka reactors were designed to withstand such anticipated Tokai earthquake and had design basis S1 of 450 Gal and S2 of 600 Gal. Units 3 & 4 were originally designed for 600 Gal, but the Ss standard established in September 2007 required 800 Gal. Since then units 3-5 have been upgraded to the new Ss standard of 1000 Gal. In August 2009 a magnitude 6.5 earthquake nearby automatically shut down Hamaoka 4 & 5, with ground motion of 426 Gal being recorded at unit 5. Some ancillary equipment was damaged.

Hamaoka units 1 & 2 had been shut down since 2001 and 2004 respectively, pending seismic upgrading – they were originally designed to withstand only 450 Gal. In December 2008 the company decided to write them off and build a new one to replace them. Modifying the two 1970s units to new seismic standards would have cost about US$ 3.3 billion and been uneconomic, so Chubu opted for a US$ 1.7 billion write-down instead.

South Korea's new APR-1400 reactor is designed to withstand 300 Gal seismic acceleration. The older OPR is designed for 200 Gal but is being upgraded to at least 300 Gal so as to be offered to Turkey and Jordan.

### Japan 1995 - Kobe

Newspaper coverage of the magnitide 7.2 Kobe earthquake which devastated Kobe and the surrounding region on 17 January 1995 raised concerns about the safety of nuclear power plants in the affected area. Horizontal ground acceleration was measures at 817 Gal – more intense than expected - and vertical acceleration was 332 Gal.

In fact none of the power reactors within 200 km of the earthquake epicentre sustained any damage and those running at the time continued to operate at capacity. Takahama and Ohi are located approximately 130 km from the epicentre of the earthquake, on the Pacific Ocean side of the Island of Honshu. Mihama is approximately 180 km away. The research reactors in the region, in Osaka and Kyoto, were also reported to be unaffected by the earthquake.

### Taiwan 1999 - Chichi

The shallow magnitude 7.6 earthquake in central Taiwan on 21 September 1999 killed thousands of people. It caused three reactors at Chinshan and Kuosheng in the north of the island to shut down automatically. They were cleared to restart two days later. A fourth reactor there was being refuelled. The two reactors at Maanshan in the south continued operating, but

reduced power later due to damage to distribution facilities. A major concern following the earthquake was how quickly power could be restored to industry.

### Japan 2005 - Miyagi

On 16 August 2005 Tohuku's three Onagawa reactors shut down automatically when a magnitude 7.2 earthquake hit northeast Honshu. They were set to trip at 200 Gal, against S1 design basis of 250 Gal (which was reached) and S2 PGA of 350-400 Gal. No damage occurred in any major part of the plant.

Onagawa-2 restarted in January 2006 after comprehensive checks and confirming that an S2 figure of 580 Gal would be safe for that unit (equivalent to magnitude 8.2). Geotechnical analysis and safety evaluation proceeded under NISA, which approved a report from the company. Unit 3 restarted in March 2006, and the smaller unit 1 restarted in May 2007.

### Japan 2007 - Niigataken Chuetsu-Oki

On 16 July 2007 the magnitude 6.8 Niigata Chuetsu-Oki earthquake occurred with epicentre only 16 km from Tepco's Kashiwazaki Kariwa 7965 MWe nuclear power plant. Local geological factors contributed to a magnification of the seismic intensity at the plant. The plant's seismometers measured PGA of 270 to 680 Gal (a later report said 829 Gal for unit 1), the S1 design bases for different units being 170 to 270 Gal and the S2 figure about 450 Gal. The peak ground acceleration thus exceeded the S1 design values in all units - hence the need to shut down, and the S2 values in units 1, 2 and 4. Four reactors shut down automatically at the pre-set level of 120 Gal, another three were not operating at the time. All the functions of shutdown and cooling worked as designed.

While there were many incidents on site due to the earthquake, none threatened safety and the main reactor and turbine units were structurally unaffected. Analysis of primary cooling water confirmed that there was no damage to the fuel in reactor cores. However, the plant will remain closed until full investigation is complete and safety confirmed, probably mid 2008. It appears that the four older units may have been more vulnerable than units 5-7 which are located 1.5 km further away.

The Ministry of Economy Trade & Industry (METI) then set up a 20-member Chuetsu Investigation and Countermeasures Committee to investigate the specific impact of this earthquake on the power station, and in the light of this to identify what government and utilities must address to ensure nuclear plant safety. It acknowledged that the government was responsible for approving construction of the first Kashiwazaki Kariwa units in the 1970s very close to what is now perceived to be a geological fault line. NISA invited the International Atomic Energy Agency to join it, the Nuclear Safety Commission and Tepco in reviewing the situation. A report was presented to the IAEA Senior Regulators' Meeting in September 2007, and a further IAEA visit was made early in 2008.

NISA released its assessment of the safety significance of earthquake damage in November. The worst of the damage rated zero on the International Nuclear Event Scale (INES), having no safety significance. Other damage was deemed not relevant to nuclear safety. The seven main reactor units themselves were still being checked, but appeared undamaged. In May 2008 Tepco adopted a new standard of 2280 Gal (2.33g) maximum design basis seismic motion for Kashiwazaki Kariwa units 1-4, over five times the previous S2 figure, and 1156 Gal (1.18g) for units 5-7, in the light of local geological factors. This standard will be reviewed by NISA and NSC. Meanwhile construction works will be undertaken to bring all units up to be able to withstand a quake producing PGA of 1000 Gal.

Tepco posted a loss of JPY 150 billion (US$ 1.68 billion) for FY2007 (to 31/3/08) due to the prolonged closure of the plant, followed by JPY 109 billion loss in the first half of FY2008. While no damage to the actual reactors has been found, detailed checks continue, and upgrading of earthquake resistance is required. Major civil engineering works are also required before the reactors resume operation. Overall, the FY2007 impact of the earthquake was projected to be JPY 603.5 billion ($5.62 billion), three quarters of that being increased fuel costs to replace the 8000 MWe of lost capacity. NISA approved the utility's new seismic estimates in November 2008, and conducted final safety reviews of the units as they were upgraded. Unit 7 restarted in May, and unit 6 in August 2009.

### Other experience

Earthquakes have previously occurred in the vicinity of a number of Japanese and other power reactors without adverse effect.

In two decades to 2004, no Japanese reactor had been tripped by the seismic detectors. In those cases where the plant automatically shutdown ("tripped") as a safety precaution, it was because of the impact of the earthquake on the operating characteristics of the plant.

In November 1993, a magnitude 5.8 earthquake in northeast Honshu produced a ground acceleration of 121 Gal at Tohuku's Onagawa-1 power reactor (497 MWe, BWR), located 30 km from the epicentre. The design conditions for the S1 and S2 events at the site were 250 and 375 Gal respectively and the reactor was set to trip at a measured peak ground acceleration (PGA) of 200 Gal. In fact it tripped at a lower level due to variations in the neutron flux outside the set parameters.

In May 2003 a magnitude 7.1 earthquake further from the same Onagawa plant produced ground acceleration of 225 Gal which tripped unit 3 (units 1 & 2 were not operating).

In October 2004 a magnitude 6.8 earthquake in Niigata Prefecture 250 km north of Tokyo had no effect on the nearby Kashiwazaki Kariwa nuclear plant, but a magnitude 5.2 quake there two weeks later caused one of the reactors - unit 7 -to trip.

In March 2005 a magnitude 7.0 earthquake in northern Kyushu did not affect the nearby Genkai and Sendai nuclear plants, nor Shimane and Ikata.

The magnitude 7.8 earthquake off the coast of Hokkaido in July 1993, had no effect on nuclear facilities. Tomari 1 and 2 reactors (550 MWe, PWRs), located 95 km from the epicentre, continued normal operation.

In December 1994, a magnitude 7.5 earthquake struck northern Japan but caused no damage to the 11 boiling water reactors or the nuclear fuel facilities in the vicinity. All operated normally.

Reactors of both western and Soviet design have been subjected to major seismic activity in North America and Europe without damage. California's power reactors, San Onofre 2 and 3 (1,070 and 1,080 MWe, PWRs) and Diablo Canyon 1 and 2 (1,073 MWe and 1,087 MWe, PWRs) continued to operate normally during the 6.6 magnitude earthquake in January 1994. San Onofre, the closer station, was about 112 km from the epicentre.

In December 1988, a magnitude 6.9 earthquake, resulting in the deaths of at least 25,000 people, occurred in northwestern Armenia. It was felt at the two-unit Armenian nuclear power station located approximately 75 km south of the epicentre, but both Soviet-designed PWRs operated normally and no damage was reported. This was the first Russian nuclear power plant specifically adapted for seismic areas, and it started operating in 1976.

In May 2008 a magnitude 7.9 earthquake affected southwestern Sichuan province in central China. The main nuclear facilities affected were military ones, apparently without any radioactive releases. About 250 km from the epicentre the Yibin fuel fabrication plant which produces both power reactor and research reactor fuel assemblies was undamaged. China's power reactors were all at least 900 km from the epicentre.

## Tsunamis

Large undersea earthquakes often cause tsunamis - pressure waves which travel very rapidly across oceans and become massive waves over ten metres high when they reach shallow water, then washing well inland. The December 2004 tsunamis following a magnitude 9 earthquake in Indonesia reached the west coast of India and affected the Kalpakkam nuclear power plant near Madras/Chennai. When very abnormal water levels were detected in the cooling water intake, the plant shut down automatically. It was restarted six days later.

Even for a nuclear plant situated very close to sea level, the robust sealed containment structure around the reactor itself would prevent any damage to the nuclear part from a tsunami, though other parts of the plant might be damaged. No radiological hazard would be likely.

Sources:
paper originally prepared by Nuclear Services Section, External Affairs, ANSTO;

Nuclear Safety Commission Sept 2006, Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities < http://www.nsc.go.jp/english/taishin.pdf>

JAIF
Tepco