After the Deluge

Short and Medium-term Impacts of the Reactor Damage Caused by the Japan Earthquake and Tsunami

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Report Summary

This report is a rapid response evaluation of the implications of the March 11, 2011 earthquake and consequent tsunami off the northeast coast of Japan. It focuses on Japan's electricity system, its energy security, and the future of the nuclear power plants located in the earthquake- and tsunami-affected regions.

It will be updated in the near future as the situation concerning the Fukushima I and II nuclear power plants become clearer, for better or worse, and as more information becomes available about other consequences of the earthquake, the tsunami, the nuclear crisis, and their interactions.

In addition to this introduction, this report presents five substantive sections.

Section 2 provides an up-to-date (as of March 17, 2011, Tokyo time) overview of the status of the nuclear fuel facilities in Japan that were affected by the earthquake and tsunami on March 11, 2011, with particular attention to the reactors and spent fuel ponds at Fukushima I reactor complex.

Section 3 reviews the implications of the damage described in section 1 for electricity supply in the Tokyo Electric Power Company (TEPCO) and Tohoku Electric Power Company service areas. First it accounts for the status of nuclear and non-nuclear power stations that generate electric power in these systems. Next, it examines how these two companies are managing demand, both immediately and into the near and medium-term, given the abrupt loss of generation capacity.

Section 4 appraises how these two power systems may evolve over the coming years, outlining a best case, baseline case, and worst case scenario. None of these scenarios are able to deliver as much electricity as was the case prior to the March 11, 2011 earthquake. All of them, to varying degrees, entail recovery and restarting of damaged nuclear and non-nuclear facilities, but the shortfall in generating capacity varies considerably in the scenarios, and all require careful management of endues and a substantial investment in increasing endues efficiency, both technically, and via modification of the demand profiles of endusers (by forced reductions, and by conservation measures taken voluntarily).

Section 5 assesses the immediate impact on the prospects for nuclear power in East and Southeast Asia-Australia, where the primary growth in nuclear power was forecast before March

11, 2011—especially in China. Some direct and indirect impacts of Japan's nuclear disaster on geopolitical security, especially in relation to North Korea, are noted in this chapter.

Section 6 evaluates the stabilization and recovery of the hardest hit sites, at Fukushima I reactor complex. It notes the possible need for a massive international effort, perhaps mandated by the UN Security Council, to assist Japan in the huge task of dealing with multiple reactors and spent fuel ponds affected by the earthquake, explosions, meltdowns, and radioactive contamination

The writing of this first version was completed late on March 17, Tokyo time. It was produced by a team of analysts and editors: Takase Kae in Tokyo; David von Hippel in Eugene; Arabella Imhoff, Peter Hayes and Richard Tanter in Melbourne; Yi Kiho in Seoul; Wen Bo in Beijing; Jungmin Kang in Virginia; Gordon Thompson in Boston: and Scott Bruce and Joan Diamond in San Francisco.

After reviewing the dire state of the nuclear power plants and spent fuel ponds in the areas affected by the earthquakes and tsunami, plus what is known about the radiological releases and spatial distribution thereof, we examine the implications of the damage in the nuclear power plants for the electricity system, both in the short-term, and also looking forward to the medium-term.

We find as follows with regard to:
a) Power requirements on the TEPCO and Tohoku Electric Power Company systems:

- *In 2009, TEPCO plants generated just over 300 terawatt hours, about 30 percent of which was by nuclear plants;*
- *Tohoku Electric Power Company sales in 2010 totaled about 79 TWh;*
- *These levels of generation and purchased power correspond to average power requirements over a year of 34,000 MW and 9,900 MW for TEPCO and Tohoku, respectively;*
- *TEPCO's peak power demand in 2009 was about 52,000 MW, and Tohoku's 2010 peak was about 14,500 MW.*

b) Existing and operable TEPCO and Tohoku supply-side resources:

- *Prior to the earthquake, TEPCO and Tohoku had a total of about 84,000 MW of supply-side resources (21,250 for Tohoku as of 2009, and 62,700 for TEPCO), of which 10,600 MW were pumped-storage hydroelectric facilities used to store energy and provide peaking power;*
- *7150 MW of thermal generating capacity on the TEPCO system was taken off line following the earthquake (of which at least 350 MW of that capacity has since been restored);*

- *In addition, the Tohoku thermal power plants at Souma and Haramachi (totaling 4000 MW of capacity) are apparently heavily damaged, due to flooding and equipment damage, and may take 6 months or so to bring back on line;*
- *The newer Sendai thermal power plant unit #4 (446 MW) suffered flooding, as did the 950 MW Shin-Sendai thermal plant, which was evacuated due to a fire at the nearby oil refinery;*
- *Damage to transformer, transmission, and distribution facilities on the Tohoku grid occurred as well.*

d) Demand-side resources for power companies affected:

- *Both TEPCO and Tohoku have announced power rationing programs, consisting of rolling blackouts in many areas, but exempting some regions, including earthquake-affected zones and central Tokyo;*
- *In the TEPCO area, demand management by rotating curtailments seem so far not to have been as extensive as originally expected, probably because many businesses and industries have yet to reopen and millions of consumers have lost access to power supply altogether;*
- *Lack of generation capacity will spur TEPCO and other affected companies, and their customers, to more aggressively pursue energy efficiency measures and generation of power on-site by consumers (or distributed generation) through the use of both renewable resources (such as solar PV, and solar hot water, which have the advantage of being largely coincident with peak summer power demand) or fossil resources (natural gas-fired units, for example).*

e) Medium-term Implications for TEPCO and Tohoku Service Areas:

- *The three affected Fukushima I reactors will not be reparable, and it may well be, given the explosion at Fukushima I unit 4, that a combination of damage and radioactive contamination at units 4 through 6 will render those units un-repairable as well;*
- *It is possible that other nuclear plants—a total of seven TEPCO, four Tohoku, and one Japan Atomic Power (the 1100 MW Tokai unit 2) nuclear reactor units, as well as a number of coal- and gas-fired plants, all of which went off-line following the earthquake—will also be affected, and be either un-repairable or require lengthy repairs;*
- *TEPCO and Tohoku will need to rely on existing fossil fuel plants much more heavily, probably for many years, than they would have had they been able to use the nuclear plants.*

We further analyze scenarios for how the TEPCO and Tohoku power systems will recover over the coming years. In our best case scenario, we find that:

- *About 4700 MW of nuclear generating capacity is gone, and must be replaced or otherwise compensated for by supply- or demand-side resources. Further, 2700 MW of* *capacity that were to be developed at Fukushima I during the next decade seem highly unlikely to be completed, and the generation that would have come from those units will need to be replaced or compensated;*

- *Another 6600 MW of nuclear capacity is likely to be offline for one to three years, 3300 MW at the Kashiwazaki-Kariwa plant is offline for inspection, and 4000 MW of thermal capacity seems likely to be offline through the summer;*
- *For the TEPCO service area, the annual output of remaining operating nuclear units totals 4912 MW (this is the TEPCO nuclear capacity as of 3/17/11 that was not affected by the earthquake and subsequent events);*
- *Given that TEPCO's hydroelectric generating capacity is virtually all "pumped-storage" hydro, that is, hydroelectric capacity built to provide peaking power for the system by storing baseload (night-time) coal-fired and nuclear energy, virtually all non-nuclear generation will be fossil-fueled;*
- *If demand in 2011 is similar to 2009 levels, TEPCO's thermal plants would be called upon to produce about 260 TWh of output in 2011, which implies a impossible capacity factor of nearly 100% for the thermal power plants available now, and a still-very-high 81% if all of the thermal power plants that were shut down during the earthquake are restarted quickly;*
- *Viewed from the perspective of peak demand, the short-term situation is even more constrained. TEPCO's peak demand in 2009 was apparently about 52 GW. This is a few GW greater than the total capacity of all of the TEPCO units available, including all thermal plants on the TEPCO system (assuming that all are available, including those shut down during the earthquake) plus the available remaining nuclear units, plus all of the pumped-storage hydro capacity;*
- *This implies that a combination of peak demand reduction measures, coupled with the decrease in electricity demand resulting from earthquake damage to infrastructure and the economy, will be required to get the TEPCO system through the next few years, even in this "Best Case" scenario;*
- *In the Best Case scenario, assuming no significant damage is found in the review of the other nuclear and thermal plants that have been shut down, when those plants are restarted, in perhaps one to three years, much or all of the short-term electricity supply shortage in the area may be eliminated, especially, if new fossil-fueled plants (such combined-cycle natural gas plants, which can be constructed in a few years if gas supplies are adequate) are built starting very soon;*
- *We have not yet done the same preliminary analyses of scenarios for the smaller Tohoku electricity system, but we would expect to find similar results to that for the TEPCO system.*

In our base case scenario, we find that:

- *Nuclear plants (other than Fukushima I) in the earthquake-affected area will undergo more lengthy inspection, and/or inspections turn up problems that must be addressed, and/or local political opposition delays restarting the plants, and/or inspections at some thermal plants also turn up problems that mean that they are out of service longer, or need to be replaced;*
- *In this case, the supply shortfall for the two companies is likely to last longer, perhaps several years longer (around five years total), and would need to be ameliorated by a combination of much more thermal generation, construction of new thermal generation plants (assuming availability of fuel), and probably a significant effort to curb net demand for both electrical energy and peak power;*
- *Curbing demand could take the form of rotating power cuts, agreements with industry to curtail consumption at peak times (or, in fact, to move elsewhere, as unappealing as that is for the local economy), aggressive energy efficiency programs (which would have the added benefit of reducing fuel requirements and costs), and/or encouraging residents, businesses, and industries to develop on-site generation, including solar photovoltaic (PV) generation, and gas-fired combined heat and power systems;*
- *Though northern Japan is not ideally suited to solar power production, solar PV generation offers an advantage that it will provide the most power in times of peak summer electricity demand in Japan, helping to reduce the summer peak that central electricity generating stations will need to handle.*

In our worst case scenario, we find that:

- *All of the nuclear power plants in the earthquake area are found to have significant seismic or other damage, leading to prolonged (more than 5 years) retrofit requirements, and some thermal plants are found to have been compromised to the point where they cannot be repaired, and must be replaced (requiring several years);*
- *In addition, the results of inspections at the earthquake-affected power plants, coupled with nationwide public concern about the safety of nuclear plants, causes other nuclear plants (apart from the earthquake-affected plants) in the TEPCO/Tohoku service areas and maybe elsewhere in Japan to be taken off line on a rotating basis for damage assessment and/or earthquake retrofit. These additional conditions would likely result in the need for many more new thermal plants (and related fuel supplies), and an even higher reliance on demand-side measures (including power rationing) than in the base case to balance available supply and demand over five to ten years.*

We suggest that the "next steps" in the power sector response should include consideration of the following issues:

- *Japan may wish to examine carefully the costs of establishing a nationally integrated "smart grid" that enables intermittent renewables to be scaled up alongside a massive program of fast, super-efficient end use efficiency in all sectors;*
- *This approach may be cheaper, faster, and more resilient in the short and the long-run than relying on coastal coal and nuclear-fired power plants to make up for the immediate and long-term shortfalls in generating capacity.*

In the fifth section of this report, we review some of the implications for the future use of nuclear power in East Asia in light of the disasters in Japan in the nuclear plants.

We find that:

- *China's State Council met March 16, 2011 to discuss the Japan nuclear crisis and to consider China's own nuclear planning, and reportedly decided to halt its plan to build new nuclear power plants, ordered a re-examination of the safety risks of nuclear power stations currently under construction, and decided to enhance the management of safety aspects of a nuclear power stations currently in operation in China;*
- *Chinese newspapers published a map outlining names and locations of all proposed Chinese nuclear plants, plants under construction, and those in operation. This is the first publicly released information on China's nuclear industry and planning. For the first time the Chinese public is able to know about many of these new nuclear plants and their locations;*
- *On March 15th, South Korea's monthly civil defence training, which usually aims at preparing for sudden attack from North Korea, instead focused on preparation for facing earthquake and tsunami disasters;*
- *Domestically, the Japanese nuclear crisis provoked sharp division between the government and opposition political parties and civil society critics of South Korea's nuclear power system;*
- *Opposition legislators in South Korea called for reconsideration of the nuclear power building plan, and particularly called attention to the fact that Korean nuclear facilities are at present built only to resist an earthquake of 6.5 on the Richter scale;*
- *It is unclear whether the nuclear crisis in Japan might affect North Korea's plans to move ahead with its program of domestic light-water reactors. It is possible that the accident in Japan will serve to encourage the North Korean leadership to accept international technical assistance on reactor safety, if such assistance is offered. It is also possible that South Korea and the United States may take a very hard line indeed against an attempt by the North to complete and turn on a small light water reactor in 2012 that is upwind and would be of highly dubious quality and reliability;*

- *Southeast Asia is often spoken of as the leading edge of a nuclear renaissance, in as much as a number of governments are in varying stages of moving towards nuclear power. Government and industry proponents of these nuclear plans in Malaysia, Singapore, and Indonesia dismissed suggestions that the Japanese nuclear crisis would have a negative influence on planning;*
- *Australia has a particular relationship to the Fukushima crisis: not only is Japan a major market for Australian uranium exports, but Tokyo Electric Power also has a strong relationship with the Australian uranium industry, including until recently a major share in the Honeymoon uranium mine. Share prices of Australian uranium mining companies plummeted, although some executives dismissed any suggestion of a long-term influence. Critics of uranium mining emphasised the direct links to the Japanese crisis through the flow of Australian uranium directly to the Fukushima reactors.*

In conclusion, we analyze the huge challenge posed by the virtual destruction of the Fukushima I reactor complex by earthquake, fire, explosions, and radiological contamination. We find that:

- *Site stabilization and recovery of the damaged and contaminated sites will take years, possibly as long as a decade, and will cost far more than constructing the plants;*
- *The necessary techniques exist, having been developed at Three Mile Island, Chernobyl, and in the routine commissioning of retired reactors;*
- *The stabilization and recovery effort likely will require an international mobilization of necessary hardware, equipment, and trained personnel, and may need a UNSC mandate to establish authority and funding management for the cleanup.*

Although we have labored hard to produce an accurate accounting of the impact of this disaster on Japan and the region, we recognize that data and analysis produced this quickly is inevitably error-prone. Naturally, we request readers to notify us of any such errors.

Finally, our heartfelt condolences go to the Japanese people who are suffering from this combined natural and technological disaster and have commenced recovery with amazing calm and courage in the face of such calamity.

Table of Contents

1. Introduction

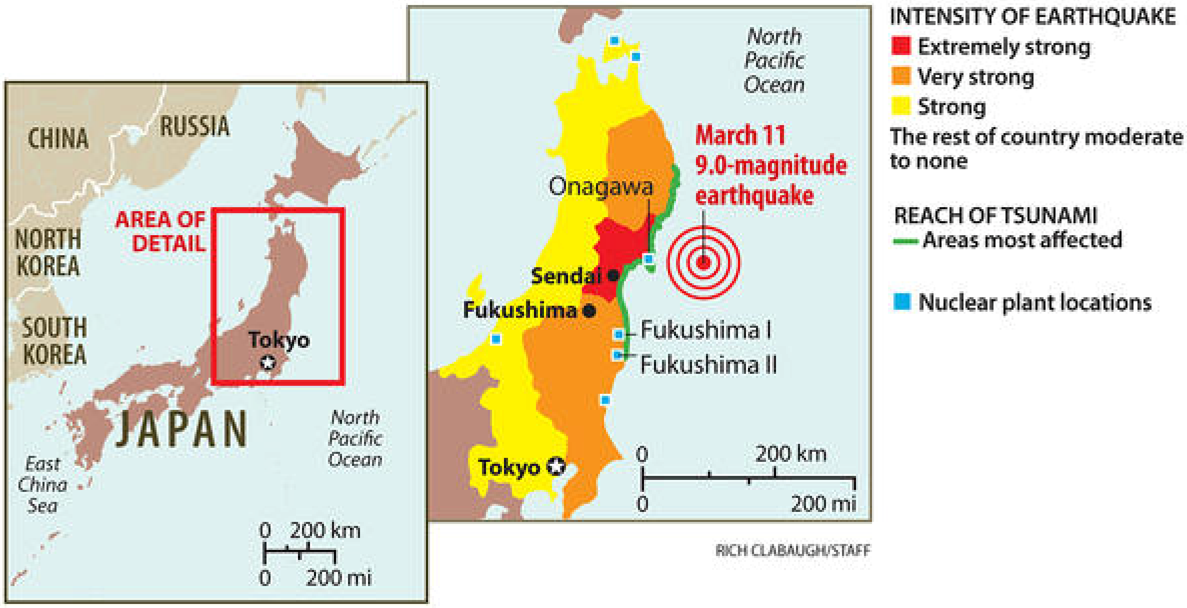
This report is a rapid response evaluation of the implications of the March 11, 2011 earthquake and consequent tsunami off the northeast coast of Japan, focusing on Japan's electricity system, its energy security and the future of the nuclear power plants located in the earthquake- and tsunami-affected regions. It will be updated in the near future as the situation concerning the Fukushima I and II nuclear power plants becomes clearer, for better or worse, and as more information becomes available about other consequences of the earthquake, the tsunami, the nuclear crisis, and their interactions. Writing of this first version was completed late on March 17, Tokyo time.

2. The state of the nuclear power plants in the earthquake/tsunami-affected area

An earthquake of magnitude 9.0 occurred at 2.46 pm local time on March 11, 2011 at a depth of 32 km in the Pacific Ocean 130 km east of the industrial city of Sendai on Honshu.[1] This earthquake is the most powerful experienced in Japan, and was followed by many aftershocks of considerable magnitude. (Figures 1 and 2). At the time of writing these were continuing, and there was a high likelihood of further substantial shocks. The effects of the earthquake in Pacific coastal regions of northeast Japan were greatly exacerbated by the tsunami generated by the earthquake which hit the coast some minutes later at heights of 10 metres or more.

[1] Location: 38.322°N, 142.369°E. For details see United States Geological Service, "*Magnitude 9.0 - NEAR THE EAST COAST OF HONSHU, JAPAN 2011 March 11 05:46:23 UTC,"*, [retrieved 15 March 2011] <http://earthquake.usgs.gov/earthquakes/eqinthenews/2011/usc0001xgp/#details>; and "*2011 Sendai earthquake and tsunami,"* Wikipedia. [retrieved 15 March 2011] <http://en.wikipedia.org/wiki/Sendai_tsunami>

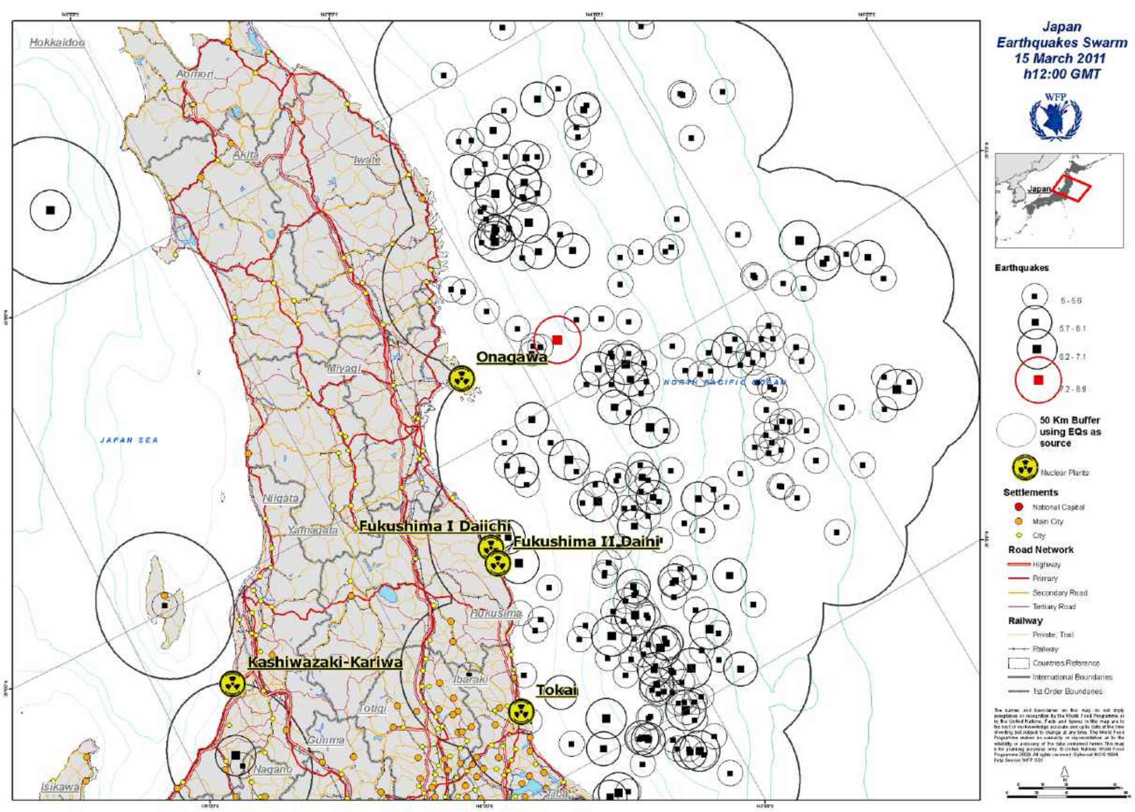
Figure 1: Areas and Nuclear Plants Affected by Earthquake and Tsunami[2]



Although the original massive 9.0 earthquake occurred northeast of the Fukushima I and II nuclear power plants, the days following saw a large number of ongoing frequent and often powerful earthquakes bracketing the area immediately offshore from the plants. Tsunami warnings were frequently issued, and although no severe tsunamis subsequently struck this region, there remains considerable concern for a further earthquake close to the plants, with the capacity to disrupt even further the consequences of the combined original earthquake and tsunami.

[2] "Japan's Nuclear Crisis: A Timeline of Key Events", *The Christian Science Monitor*, [retrieved 15 March 2011] <http://www.csmonitor.com/World/Asia-Pacific/2011/0315/Japan-s-nuclear-crisis-A-timeline-of-key-events>

Figure 2: Japan: Earthquakes Swarm (15 March 2011)[3]



When the earthquake occurred there were 54 nuclear power stations in operation (Figure 4). Five sets of nuclear reactors were affected by the earthquake: (from north to south) Onagawa, Fukushima I, Fukushima II, Higashidori, and Tokai. The locations of the plants most affected by the earthquake and tsunami are shown in Figure 1. When the earthquake hit, safety systems at the reactors automatically triggered control rods, which successfully shut down the nuclear chain reactions at the plants affected by the earthquake. The key to the subsequent developments at a number of the reactors in the affected zone was the ongoing generation of heat in reactors that had been shut down. The decay of radioactive atoms in the fuel in a reactor core, continues even

[3]See original site for a large resolution version.
United Nations World Food Programme (WFP), "Japan: Earthquakes Swarm (15 Mar 2011)," *Relief Web*, [retrieved 17 March 2011]
<http://www.reliefweb.int/rw/rwb.nsf/db900sid/RKRR-8EZLQD?OpenDocument&rc=3&emid=EQ-2011-000028-JPN>

after the nuclear chain reactions are shut down, and this decay generates a lot of heat, which must be removed from the core (Figure 3).

> "For an extended period after a reactor shutdown, the radioactive fission products in a reactor core generate heat at a rate great enough to turn hundreds of metric tons of water into steam per day (Figure 3). It would take only about 300 metric tons of steam to increase the pressure inside even a large (60,000 cubic meter volume) Three Mile Island type containment building by about ten atmospheres."[4]

If cooling water is not supplied to remove the heat, damage to the nuclear fuel, which consists of pellets of uranium oxide contained in long tubes made of an alloy of zirconium metal, can occur, and did in several units, as described below.

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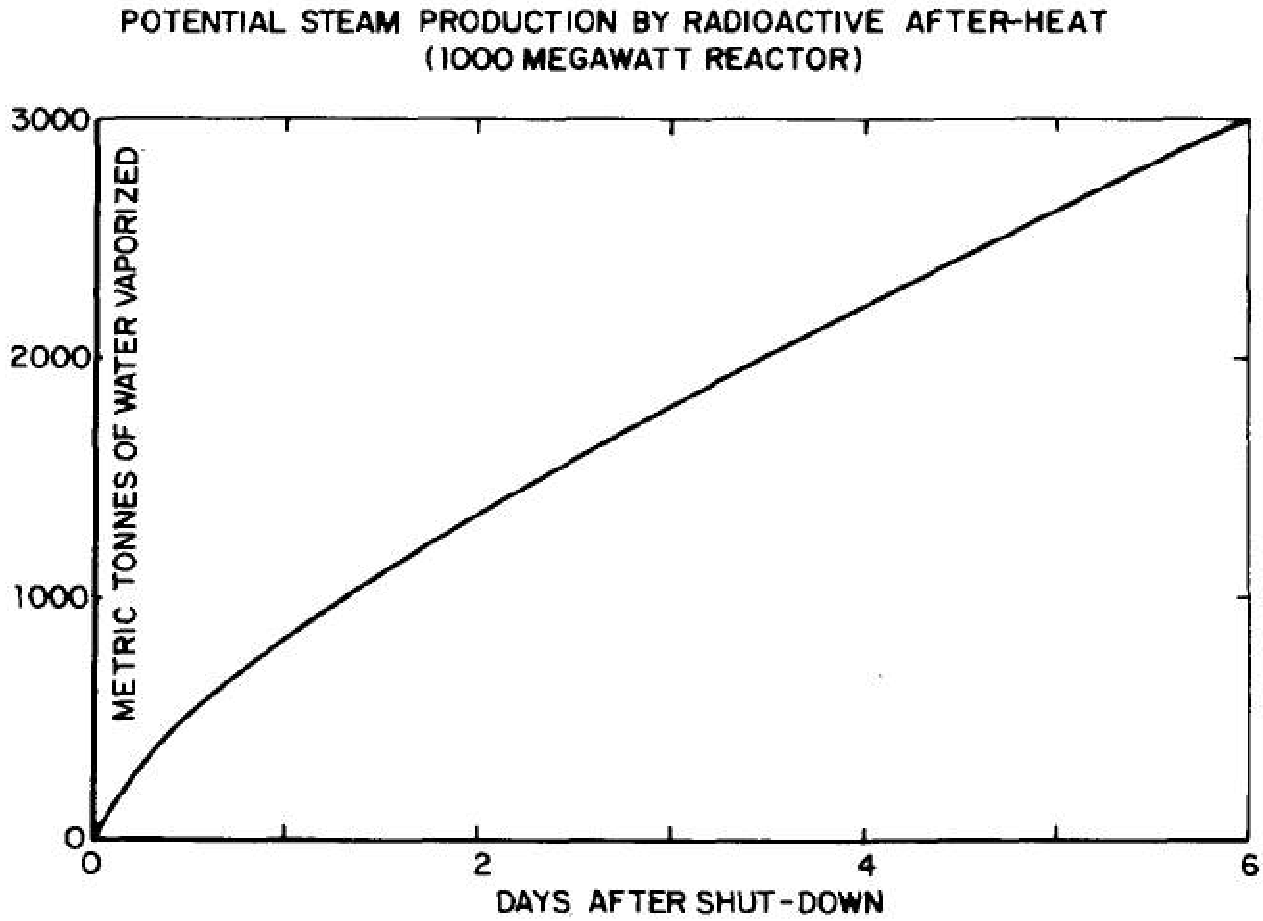
[4]Jan Beyea and Frank von Hippel, "Containment of a Reactor Meltdown," *Bulletin of the Atomic Scientists*, August/September 1982, p.51.

Figure 3: Potential steam production by radioactive after heat (1,000 MW Reactor)[5]



The figure shows the cumulative amount of water which would be evaporated by the radioactive after-heat generated after shut-down by the core of a typical modern 1,000-megawatt light water reactor. In the absence of heat removal from the containment, the steam pressure so generated would threaten the containment integrity within hours.

[5] Jan Beyea and Frank von Hippel, "Containment of a Reactor Meltdown," *Bulletin of the Atomic Scientists*, August/September 1982

Table 1: Nuclear power stations in Japan (as of 2008) - table[6]

Status	Licensee	Power Station Name	Unit Number	Reactor Type	Licensed Capacity (MWe)	Start Date of Construction	Start Date of Operation
Operating	Japan Atomic Power Co.	Tokai-Daini		BWR	1,100	Apr. 1973	Nov. 1978
		Tsuruga	No. 1	BWR	357	Feb. 1967	Mar. 1970
			No. 2	PWR	1,160	Mar. 1982	Feb. 1987
	Hokkaido E. P. Co.	Tomari	No. 1	PWR	579	Aug. 1984	Jun. 1989
			No. 2	PWR	579	Aug. 1984	Apr. 1991
	Tohoku E. P. Co.	Onagawa	No. 1	BWR	524	May 1971	Jun. 1984
			No. 2	BWR	825	Jun. 1989	Jul. 1995
			No. 3	BWR	825	Sep. 1996	Jan. 2002
		Higashidori	No. 1	BWR	1,100	Dec. 1998	Dec. 2005
	Tokyo E. P. Co.	Fukushima-Daiichi	No. 1	BWR	460	Sep. 1967	Mar. 1971
			No. 2	BWR	784	May 1969	Jul. 1974
			No. 3	BWR	784	Oct. 1970	Mar. 1976
			No. 4	BWR	784	May 1972	Oct. 1978
			No. 5	BWR	784	Dec. 1971	Apr. 1978
			No. 6	BWR	1,100	Mar. 1973	Oct. 1979
		Fukushima-Daini	No. 1	BWR	1,100	Aug. 1975	Apr. 1982
			No. 2	BWR	1,100	Jan. 1979	Feb. 1984
			No. 3	BWR	1,100	Nov. 1980	Jun. 1985
			No. 4	BWR	1,100	Nov. 1980	Aug. 1987
		Kashiwazaki-kariwa	No. 1	BWR	1,100	Nov. 1978	Sep. 1985
			No. 2	BWR	1,100	Aug. 1983	Sep. 1990
			No. 3	BWR	1,100	Jun. 1987	Aug. 1993
			No. 4	BWR	1,100	Jun. 1987	Aug. 1994
			No. 5	BWR	1,100	Aug. 1983	Apr. 1990
			No. 6	ABWR	1,356	Aug. 1991	Nov. 1996
			No. 7	ABWR	1,356	Aug. 1991	Jul. 1997
	Chubu E. P. Co.	Hamaoka	No. 3	BWR	1,100	Jun. 1982	Aug. 1987
			No. 4	BWR	1,137	Oct. 1988	Sep. 1993
			No. 5	ABWR	1,267	Mar. 1999	Jan. 2005
	Hokuriku E. P. Co.	Shika	No. 1	BWR	540	Nov. 1988	Jul. 1993
			No. 2	ABWR	1,358	Aug. 1999	Mar. 2006
	Kansai E. P. Co.	Mihama	No. 1	PWR	340	Aug. 1967	Nov. 1970
			No. 2	PWR	500	Dec. 1968	Jul. 1972
			No. 3	PWR	826	Jul. 1972	Dec. 1976
		Takahama	No. 1	PWR	826	Apr. 1970	Nov. 1974
			No. 2	PWR	826	Feb. 1971	Nov. 1975
			No. 3	PWR	870	Nov. 1980	Jan. 1985
			No. 4	PWR	870	Nov. 1980	Jun. 1985
		Ohi	No. 1	PWR	1,175	Oct. 1972	Mar. 1979
			No. 2	PWR	1,175	Nov. 1972	Dec. 1979
			No. 3	PWR	1,180	Mar. 1987	Dec. 1991
			No. 4	PWR	1,180	Mar. 1987	Feb. 1993
	Chugoku E. P. Co.	Shimane	No. 1	BWR	460	Feb. 1970	Mar. 1974
			No. 2	BWR	820	Feb. 1984	Feb. 1989
	Shikoku E. P. Co.	Ikata	No. 1	PWR	566	Apr. 1973	Sep. 1977
			No. 2	PWR	566	Dec. 1977	Mar. 1982
			No. 3	PWR	890	Aug. 1986	Dec. 1994
	Kyushu E. P. Co.	Genkai	No. 1	PWR	559	Mar. 1971	Oct. 1975
			No. 2	PWR	559	May 1976	Mar. 1981
			No. 3	PWR	1,180	Mar. 1985	Mar. 1994
			No. 4	PWR	1,180	Mar. 1985	Jul. 1997
		Sendai	No. 1	PWR	890	Nov. 1978	Jul. 1984
			No. 2	PWR	890	Mar. 1981	Nov. 1985
		Total		(53 Units)	47,935		
Under Construction	Hokkaido E. P. Co.	Tomari	No. 3	PWR	912	Nov. 2003	Dec. 2009*
	Chugoku E. P. Co.	Shimane	No. 3	ABWR	1,373	Dec. 2005	Dec. 2011*
	E. P. Development Co.	Ohma		ABWR	1,383	May 2008	Nov. 2014*
		Total		(3 Units)	3,668		
On Planning Stage	Japan Atomic Power Co.	Tsuruga	No. 3	APWR	1,538	Oct. 2010*	Mar. 2016*
			No. 4	APWR	1,538	Oct. 2010*	Mar. 2017*
	Tohoku E. P. Co.	Namie-Odaka		BWR	825	FY 2015*	FY 2020*
		Higashidori	No. 2	ABWR	1,385	After FY 2015*	After FY 2020*
	Tokyo E. P. Co.	Fukushima-Daiichi	No. 7	ABWR	1,380	Apr. 2011*	Oct. 2015*
			No. 8	ABWR	1,380	Apr. 2011*	Oct. 2016*
		Higashidori	No. 1	ABWR	1,385	Dec. 2010*	Mar. 2017*
			No. 2	ABWR	1,385	After FY 2013*	After FY 2019*
	Chubu E. P. Co.	Hamaoka	No. 6	ABWR	1,400	FY 2015*	After FY 2019*
	Chugoku E. P. Co.	Kaminoseki	No. 1	ABWR	1,373	FY 2010*	FY 2015*
			No. 2	ABWR	1,373	FY 2015*	FY 2020*
	Kyushu E. P. Co.	Sendai	No. 3	APWR	1,590	FY 2013*	FY 2019*
		Total		(12 Units)	16,552		
Preparing for Decommissioning	Chubu E. P. Co.	Hamaoka	No. 1	BWR	(540)	Feb. 1971	Mar. 1976
			No. 2	BWR	(840)	Sep. 1973	Nov. 1978
Under Decommissioning	Japan Atomic Power Co.	Tokai		GCR	(166)	Mar. 1961	Jul. 1966

*Planned

[6] Japan Nuclear Energy Safety Agency, "Current Status of Nuclear Facilities in Japan," 2009, [retrieved 16 March 2011] <http://www.jnes.go.jp/english/activity/unkan/e-unkanhp1/e-unkanhp1-2009/book1/>

The three-unit **Onagawa** plant (total capacity, about 2100 megawatts electric (hereafter, MW refers to MWe unless otherwise stated)), is located nearly due west of the epicenter of the earthquake, and northeast along the coast from the Sendai area that was heavily affected by the tsunami that followed the quake. Two of the units of the plant were operating as of the time of the earthquake, and one was just being started up. Nuclear chain reactions in all three units were shut down immediately after the earthquake. Though all of the Onagawa plants sustained some damage to buildings and ancillary equipment, and in some cases emergency diesel generators were activated to power cooling water pumps, none of the damage seems to be major, and all reactors have been cooled to under 100 C and are considered stable ("cold shutdown").[7]

The six-year-old **Higashidori** plant (one operating unit of 1067 MW, with plans for three more units on the site) was offline for a routine check-up at the time of the earthquake. The plant required activation of emergency diesel power after the earthquake, and some seawater spilled into a floor of the plant from the secondary coolant loop, but the plant does not appear to have been heavily damaged.

The **Tokai** unit 2 reactor (1056 MW), on the east coast northwest of the quake epicenter, was also shut down automatically when the earthquake hit. Although a cooling pump apparently failed after at one point, a second pump took up the load, and the reactor is in cold shutdown[8].

The four-units of the **Fukushima II plant,** commissioned in the 1980s with about 4400 MW total (measured in gross electric output including power used in operating the power plant), were all operating at the time of the earthquake, and shut down automatically. There appears to have been some problems with the cooling systems operations after the earthquake, and a plant worker was injured and later died, but by March 15 all four units were reported to be stable and under cold shutdown.

Fukushima I Nuclear Power Plant

The account of the **Fukushima I plant** is complex, and at the time of writing (17 March), highly uncertain. The plant consists of six reactor units built in the 1970s, with two more units planned for the site. The total capacity of the six existing units is about 4696 MW (gross). Three of the

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[7]International Atomic Energy Agency, "Japan Earthquake Update (13 March 2011, 12:35 UTC)," [retrieved 17 March 2011], <http://www.iaea.org/newscenter/news/tsunamiupdate01.html>
[8]International Atomic Energy Agency, "Japan Earthquake Update (15 March 2011, 14:10 UTC)" and similar at Z<http://www.iaea.org/newscenter/news/tsunamiupdate01.html>.

six Fukushima I reactor units at the site were operating at the time of the earthquake. Emergency systems were supposed to provide cooling water to the reactor cores after shut down, but these systems failed, first, apparently, because of loss of off-site power due to earthquake damage, and then because of damage to back-up diesel generators caused by the tsunami that followed the earthquake. As a result, the water cooling the fuel rods began to boil, pressure in the reactor vessels rose, and steam and other gases had to be vented from the reactor vessels into the building surrounding the reactor. In units 1, 2 and 3 of the plant, hydrogen gas generated by the interaction of steam with the zirconium metal in the fuel rods exploded in the reactor building, releasing steam and at least some radioactive cesium and iodine gases. Radioactive cesium and iodine were detected at low levels by the US military 100 miles off of Japan's coast. As a last resort, seawater has been pumped into the reactor cores to try and cool them down to stable levels.

Figure 4 : Fukushima Number 1 Nuclear Power Plant

Figure 5: Layout of Fukushima Nuclear Power Plant Number I

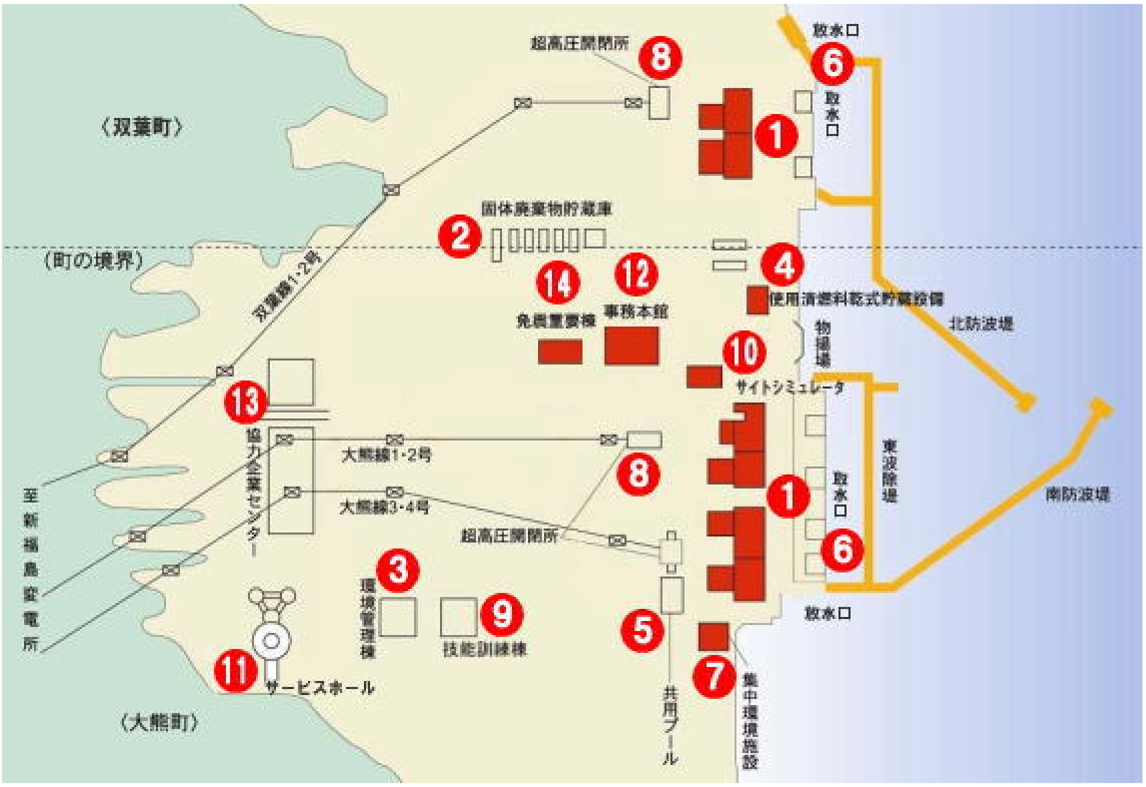

Table 2: Status of nuclear power plants in Fukushima as of 16:00 March 17[9]

Status of nuclear power plants in Fukushima as of 9:00 March 17 (Estimated by JAIF)

Power Station	Fukushima #1 Nuclear Power Station					
Unit	1	2	3	4	5	6
Electric / Thermal Power output (MW)	460 / 1380	784 / 2381				1100 /3293
Type of Reactor	BWR-3	BWR-4	BWR-4	BWR-4	BWR-4	BWR-5
Operation Status at the earthquake occurred	Service	Service	Service	Outage	Outage	Outage
Core and Fuel Integrity	Damaged	Damaged	Damaged	No fuel rods	Not Damaged	Not Damaged
Containment Integrity	Not Damaged	Damage Suspected	Damage Suspected	Not Damaged	Not Damaged	Not Damaged
Core cooling requiring AC power	Not Functional	Not Functional	Not Functional	Not necessary	Not necessary	Not necessary
Core cooling not requiring AC power	Not Functional	Not Functional	Not Functional	Not necessary	Not necessary	Not necessary
Building Integrity	Severely Damaged	Slightly Damaged	Severely Damaged	Severely Damaged	Not Damaged	Not Damaged
water level of the pressure vessel	Around half of the Fuel	Recovering after Dried up	Around half of the Fuel	Safe	Safe	Safe
pressure of the pressure vessel	Stable	Unknown (run out of battery)	Stable	Safe	Safe	Safe
Containment pressure	Stable	D/W: Unknown, S/P: Atmosphere	Stable	Safe	Safe	Safe
Water injection to core (Accident Management)	Continuing (Seawater)	Continuing(Seawater)	Continuing(Seawater)	Not necessary	Not necessary	Not necessary
Water injection to Containment Vessel (AM)	Continuing(Seawater)	to be decided(Seawater)	Continuing(Seawater)	Not necessary	Not necessary	Not necessary
Containment venting (AM)	Continuing	Preparing	Continuing	Not necessary	Not necessary	Not necessary
Fuel Integrity in the spent fuel pool	(No info)	(No info)	Level Low, Preparing Water Injection	Level Low, Preparing Water Injection Damage to Fuel Rods Suspected	Pool Temp. Increasing	Pool Temp. Increasing
Environmental effect	NPS border: 1472 μSv/h at 16:20, Mar. 16					
Evacuation Area	20km from NPS * People who live between 20km to 30km from the Fukushima #1NPS are to stay indoors.					
Remarks	A fire broke on the 4th floor of the Unit-4 Reactor Building around 6AM, Mar. 15, and the radiation monitor readings increased outside of the building. 30mSv between Unit-2 and Unit-3, 400mSv beside Unit-3, 100mSv beside Unit-4 at 10:22, Mar. 15. It is estimated that spent fuels stored in the spent fuel pit heated and hydrogen was generated from these fuels, resulting in explosion. TEPCO later announced the fire was been burned out. Another fire was observed at 5:45, Mar. 16, and then disappeared later. Other staff and workers than fifty TEPCO employees who are engaged in water injection operation have been evacuated. White smoke was seen rising from the vicinity of Unit-3 at around 8:30, Mar. 16. TEPCO estimates that failing to cool the SFP has resulted in evaporation of pool water, generating steam.					

The Japan Atomic Industrial Forum provided daily estimates of the situation at the Fukushima plants. The JAIF estimate of the situation at Fukushima as of 1400 on 17 March (Figure 5) can serve as a baseline (Table 2).[10]

- Core and fuel integrity was "damaged" in units 1, 2, and 3; units 5 and 6 "undamaged"; and unit 4 had no fuel rods in the reactor, having been recently unloaded;
- Reactor pressure integrity was "unknown" in units 1, 2, and 3;
- Damage was "suspected" to the containment vessel integrity of units 2 and 3. Primary and backup cooling facilities at units 1, 2, and 3 were "not functional";
- The integrity of the buildings in units 1, 3, and 4 were "severely damaged".
- The water level in the reactor pressure vessel covered "around half the fuel" in units 1 and 3, and "higher than half" in unit 2;
- Seawater injection was continuing to the core of units 1, 2, and 3;

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[9] Japan Atomic Industrial Forum, "Reactor Status Update 9 - Status of nuclear power plants in Fukushima as of 16:00 March 17 (Estimated by JAIF)," [retrieved 17 March 2011] <http://www.jaif.or.jp/english/news_images/pdf/ENGNEWS01_1300350525P.pdf>

[10] Japan Atomic Industrial Forum, "Reactor Status Update 9 - Status of nuclear power plants in Fukushima as of 16:00 March 17 (Estimated by JAIF)," [retrieved 17 March 2011] <http://www.jaif.or.jp/english/news_images/pdf/ENGNEWS01_1300350525P.pdf>

- Seawater injection into the containment vessel was continuing in units 1 and 3, but yet to be decided for unit 2;
- Containment venting was continuing from units 1 and 3, and in preparation for unit 2;
- Fuel integrity of the spent fuel pool for unit 3 was characterised by low levels of water, with preparations for water injection. The situation in unit 4 was more serious, with water level low and suspicion that the fuel rods in the pool had been damaged [after fires over two days].

The core of Reactor 2 seems to have been fully exposed (not covered by cooling water) on at least two occasions. On March 15, an explosion near the base of Reactor 2 in a structure designed to help cool the reactor appears to have resulted in a breach in the concrete reactor vessel containment structure, with a release of significant amounts of radioactivity, though the situation is not entirely clear. The plant's operator, Tokyo Electric Power Company (TEPCO) continues to work to inject seawater into the cores of reactors 1 through 3 to try and stabilize temperatures. As of early on March 16, it appears that this process is ongoing. As of this writing, it is assumed that a partial melting of the fuel rods in the reactor cores has occurred in the reactors 1 through 3.

A potential complicating factor to the situation above is that according to at least one source, mixed-oxide fuel was being used in unit 3 of Fukushima I since 2010. [11] Mixed oxide fuel is made from "recycled" plutonium (Pu) oxide, as well as the usual uranium oxide. Mixed oxide fuel that has been used in a reactor fuel therefore has different chemical and radiological properties than used uranium oxide fuel, and these properties may make the fuel more dangerous to public health if fuel components are released in a melt-down situation. Approximately six (6) percent of the unit 3 core was MOx fuel, containing 1.2 percent uranium-235 and 3.9 percent plutonium by weight[12]. Another worry is that the spent fuel pool at the top of the unit 3 reactor building may have been damaged by the explosion that took the top off of the unit 3 building. If so, it may increase the difficulty of maintaining cooling of the spent fuel stored there. Further, there is a concern that debris from the explosion may have fallen into the spent fuel pool and/or the arrangement of the rods in the spent fuel may have been altered by the explosion, either of which may affect the integrity of the fuel rods. (We do not, at this point, know what quantity of spent fuel may have been stored in the unit 3 spent fuel pool, or whether spent MOx fuel was stored there.)

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[11] Physicians for Social Responsibility, "Japan's Nuclear Reactor Crisis Worsens", dated March 14, 2011, and available as <http://www.psr.org/news-events/news-archive/japans-nuclear-reactor-crisis-worsens.html>.

[12] TEPCO, [Summary of reactor core configurations in Japanese], <http://www.tepco.co.jp/nu/torikumi/nuclearlibrary/atomfuel/atomfuel01-j.html>, accessed 3/17/2011.

Also on March 15, an explosion at the top of the reactor building for Fukushima I unit 4 occurred. It is believed that the explosion may have been the result of hydrogen gas build-up in the building due to the overheating of fuel rods stored in a spent fuel storage pool on the fourth floor of the building[13]. The overheating was presumably due to lack of water circulation and/or a leak in the spent fuel pool, though we do not have confirmation of the cause. The fire burned for some hours, but had been extinguished as of late on March 15. Considerable radiation has been emitted, with measured levels of radiation reaching 400 millisieverts (mSv) per hour at one point on March 15th. Radiation emissions have receded since, but the situation is still serious as of March 17, and ascertaining the status of the spent fuel pools at all of the reactors, and making sure that cooling in the pools is adequate is a top priority. Overheating and exposure of the spent fuel in those pools could ultimately lead to large releases of radioactivity.

Figure 6: Damage at Fukushima Daiichi nuclear plant, from satellite image (Digital Globe), 9:35 am local time on March 16, 2011 [14]

[13] "Radiation Leak Feared at Spent Fuel Pool, Water Injection Ordered", *Kyodo News*, March 15, 2011, <http://english.kyodonews.jp/news/2011/03/78352.html>

[14] Reuters/DigitalGlobe/Handout, "Japan Earthquake Live," *Reuters,* [retrieved 16 March 2011], <http://live.reuters.com/Event/Japan_earthquake2>

Figure 7: Damage at Fukushima Daiichi nuclear plant, from satellite image (Digital Globe), 9:35 am local time on March 16, 2011 [15]

By the night of March 17, Self Defence Force CH-47 helicopters had made a number of runs carrying 7.5 tonnes of water on each run to dump on unit 3, but the number of operations was limited by fears of radiation exposure. SDF aviation firetrucks and National Police water cannons gained access to the reactor vicinity, and poured 30 tonnes of water over a short period onto unit 3 spent fuel storage, but again suspended operations because of radiation concerns. Meanwhile the water in the spent fuel storage in unit 4 continued to heat and evaporate, but no attempt could be made to inject water effectively. Tokyo Electric Power announced that an AC mains power line would reach the site on March 18, but warned that even with mains power, pumps may be non-functional due to damage by pumping of seawater.

A sixth set of reactors, the **Hamaoka complex** south of the earthquake epicenter and north of Tokyo, was apparently somewhat affected by the earthquake, with diesel backup power required for at least one unit at one point. Of the five Hamaoka units, the two that were operating at the

[15]Reuters/DigitalGlobe/Handout, "Japan Earthquake Live," *Reuters,* [retrieved 16 March 2011], <http://live.reuters.com/Event/Japan_earthquake2>

time of the earthquake (two more units have been decommissioned, and one was offline while under inspection) are apparently operational and operating[16].

Figure 8: Schematic of Cutaway of Boiling Water Reactor Mk-I[17]

[16]" Japan Says Hamaoka Plant Safe After New Quake: IAEA", *Reuters*, 3/15/2011. http://www.reuters.com/article/2011/03/15/us-japan-nuclear-plant-idUSTRE72E5Q020110315.

[17]Nuclear Regulatory Commission, "Boiling Water Reactor (BWR) Systems, Reactor Concepts Manual," USNRC Technical Training Centre, (n.d.), p. 3-16, [retrieved 15 March 2011] <http://www.nrc.gov/reading-rm/basic-ref/teachers/03.pdf>

Figure 9: Schematic of Mark-I Boiling Water Reactor
Fukushima I NPP, Units I-1, I-2, I-3, I-4, I-5 (Japanese government) [18]

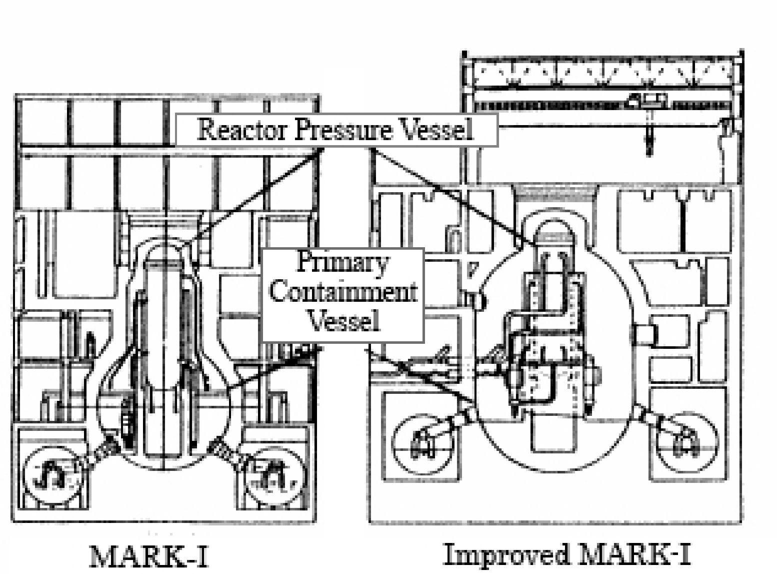
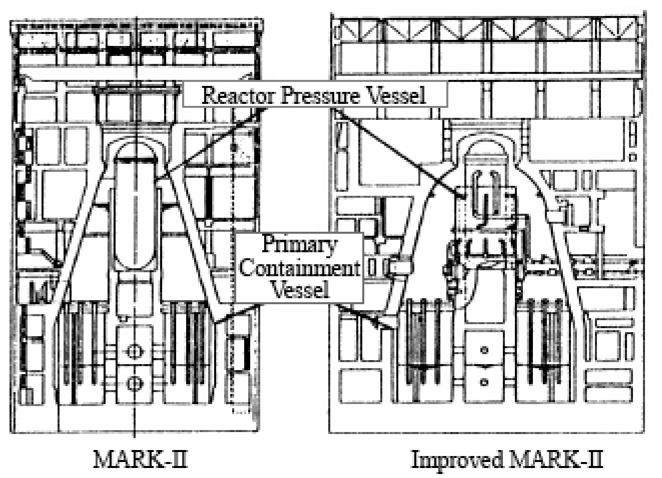
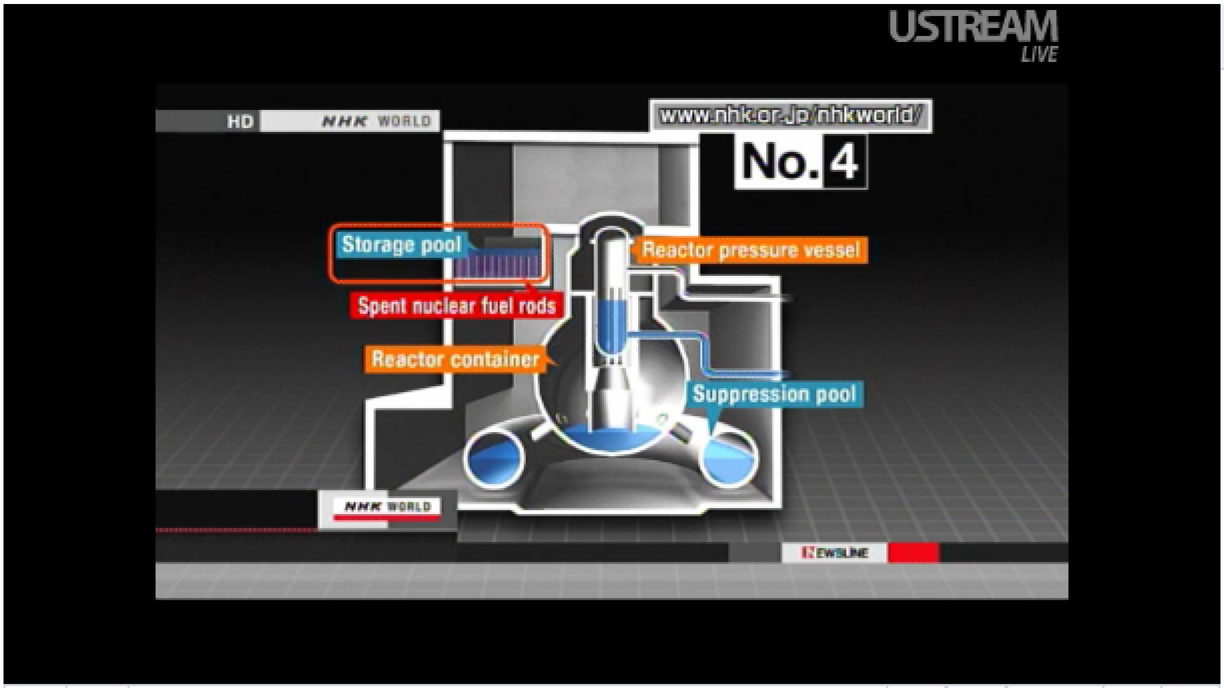


Figure 10: Schematic of Mark-II Boiling Water Reactor
Fukushima I NPP, Unit 1-6[19]



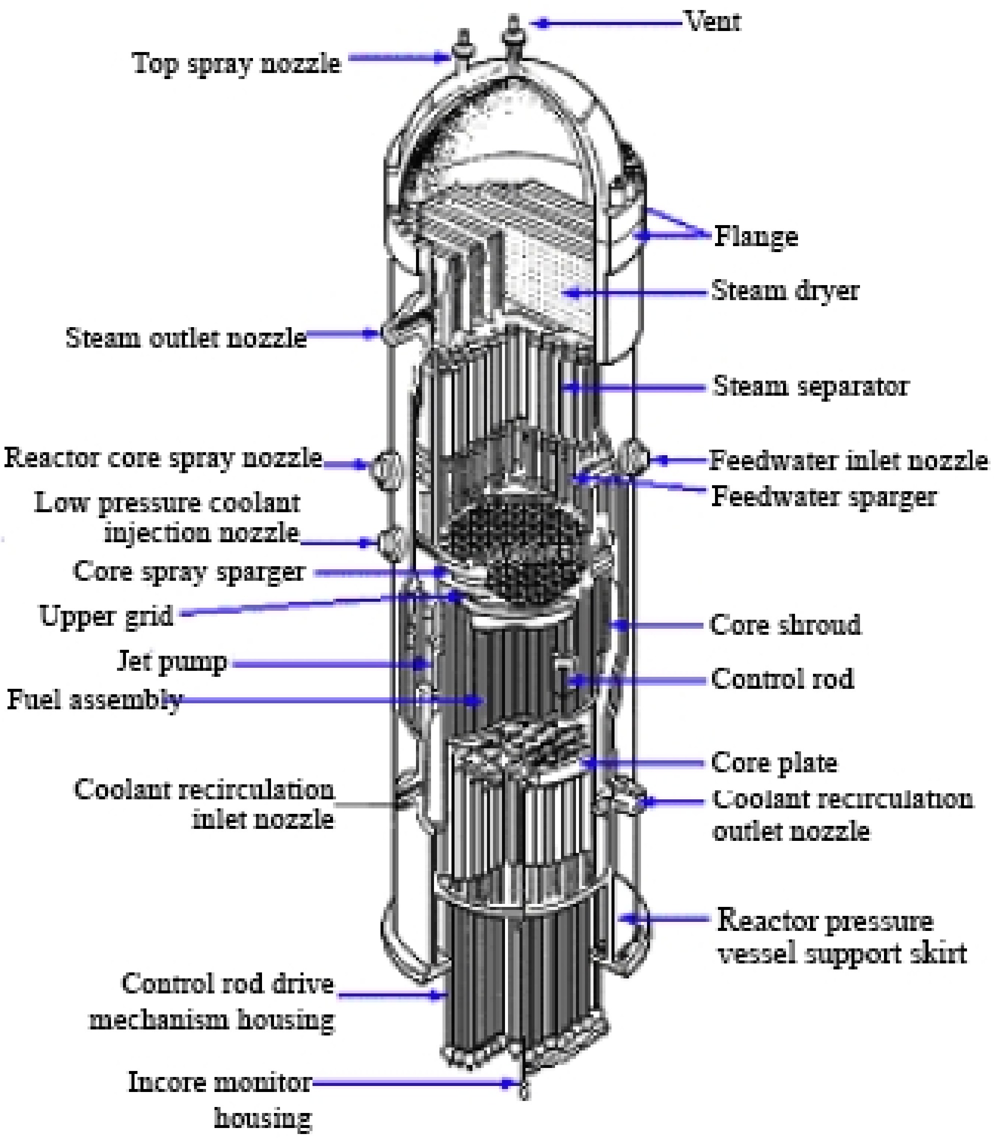
[18]Government of Japan, *National Report of Japan for the Third Review Meeting, Convention on Nuclear Safety,* August 2004, p. 18-12.
[19]Ibid.

Figure 11: Schematic of Fukushima I NPP, Unit 4, with storage pool indicated[20]



[20] USTREAM, NHK-TV live broadcast, 16 March 2011 <http://www.ustream.tv/channel/nhk-world-tv>

Figure 12: Internal structure of BWR reactor vessel[21]



[21] "Boiling Water Reactor Power Plant," *Asian Nuclear Safety Network*, September 2007, p. 6.

Rokkasho nuclear complex

The coastal village of Rokkasho in Aomori prefecture is bracketed by one of the most intensive co-location of civilian nuclear energy facilities in the world, including the large Rokkasho Reprocessing Plant with a capacity of 800 tonnes of uranium annually, and generating 8 tonnes of plutonium a year. The Reprocessing Plant alone is made up of 38 buildings covering an area of 3,800,000 sq. m. Rokkasho is also home to a MOX Fuel Fabrication Plant, a Uranium Enrichment Plant, and a Low-Level Waste Storage Center.[22] Accordingly, the question of the effects of the earthquake and the tsunami on these facilities is particularly important.

However, at the time of writing information is conflicting and ambiguous. Media and industry reports indicated that the facility lost power at the time of the earthquake, and then operated on back-up power until mains power was restored at 12.00 pm on March 15. "It was confirmed that no fire, damage to equipment, injuries to personnel occurred. Radiation levels were measured at a normal level of safety.[23] There were also reports of coolant water splashed out of the spent nuclear fuel storage pools, but no imminent fear of criticality.

However overall, the amount of information is surprisingly small for such an important facility, particularly given its location on the coast of Aomori, and a long-running dispute about the seismology of a fault line under the site.[24]

Radiological releases and consequences

The combined stock of radioactive materials in the reactors and spent fuel ponds at the Fukushima I reactor site is large. The exact quantities of fission products and other irradiated

[22] Japan's Nuclear Fuel Cycle Facilities, [retrieved 18 March 2011] <http://www.japannuclear.com/nuclearpower/fuelcycle/facilities.html>

[23] "The Federation of Electric Power Companies of Japan (FEPC) Washington D.C. Office As of 10:15AM (EST), March 16, 2011", cited by Jeffrey Lewis, "FEPC Statement on Fukushima," *Arms Control Wonk*, 13 March 2011, [retrieved 18 March 2011] , <http://lewis.armscontrolwonk.com/archive/3640/fukushima-reactor>; and "Most Recent FEPC Statement," *Arms Control Wonk*, 16 March 2011, [retrieved 18 March 2011] , <http://lewis.armscontrolwonk.com/archive/3675/most-recent-fepc-statement>

[24] According to Mitsuhisa Watanabe, in a claim disputed by Rokkasho authorities, "A reverse fault, which could cause a giant earthquake, is reaching just under the uranium-enrichment factory within the plant, while the reprocessing facility is a little apart from the fault. The factory must be moved to another place immediately." Hiroyuki Koshoji, "Japan's Nuclear Facilities Face Quake Risk," *UPI*, 12 June 2008, [retrieved 18 March 2008] <http://www.upiasia.com/Security/2008/06/12/japans_nuclear_facilities_face_quake_risk/3945/>

materials in the reactor and spent fuel ponds depends on how long fuel rods have been in the reactors, the degree of burn-up over time in the cores, and the age of spent fuel removed into storage ponds. The older the spent fuel, the more short-lived fission products have already decayed, leaving less residual radioactive materials to be released. Roughly speaking, the three reactors suffering major damage (Fukushima I, units 1, 2, 3) total about 1959 MWe, or about 2GWe. These reactors would contain about 200 metric tonnes of lightly enriched uranium; and about 6 percent of the fuel rods of unit 3 contains Mixed Oxide Fuel with recycled plutonium that was loaded in August 2010, to start generating power in late September 2010.[25]

As of March 2010, the spent fuel ponds at Fukushima contain about 2,820 metric tonnes of spent fuel in the form of spent fuel rods, of varying ages. This is distributed as 1,760 metric tonnes at Fukushima I reactor complex spent fuel pond, and 1,060 metric tonnes at Fukushima II reactor complex spent fuel ponds.[26] Thus, some fraction of the 1,760 metric tonnes has been at risk of fire and release from spent fuel ponds associated with Fukushima I, units 3 and 4, but exactly how much is not clear. However, it is likely that the radiological risk associated with the spent fuel ponds which contain many billions of curies of radiation could easily exceed that associated with the reactor cores by a factor of 5-10.[27] Thus, while the core meltdown and cooling problem likely is harder to control at the moment, the spent fuel ponds, which need to be only watered and provide some access through the exploded buildings to plant workers and air-delivered water, present a far greater radiological hazard due to the combination of cumulative radioactive materials (on the order of 59 GWe-years of reactor fuel) and lack of containment due to explosions opening the pools to the atmosphere so that thermal plumes are created directly by fires in the pools.

[25]"Fukushima Reactor Receives MOX", *Japan Times,* August 23, 2010, at: <http://search.japantimes.co.jp/cgi-bin/nn20100823a7.html>

[26]See slide 4, T.Aida, T.Hara, Y.Kumano, Tokyo Electric Power Company "Operating Experience in Spent Fuel Storage Casks," IAEA-CN-178/KN27, 3 June 2010, at: <http://www-ns.iaea.org/downloads/rw/conferences/spentfuel2010/sessions/session-ten-b/session-10b-japan-1.ppt>.

[27]Very roughly, the ratio of {1,760 tonnes of radioactive spent fuel in the spent fuel ponds, adjusted downwards for decay in the older stored fuel}/{200 tonnes of reactor fuel in the two reactors at risk, adjusted for low burn-up in at least Fukushima unit 3 since it was reloaded last 2010}.

Table 3: Storage of Spent Nuclear Fuel at Fukushima NPP I and II, as of March 2010[28]

	Number of reactors	Storage amount (ton-U)	Storage capacity (ton-U)	Occupancy (%)
Fukushima I	6	1,760	2,100	84%
Fukushima II	4	1,060	1,360	78%

How big a hazard is impossible to say at this stage. The initial relatively tiny releases of radiation that resulted in spikes in measured radiation at the plants was likely due to venting of radioactive steam to depressure the reactor cores suffering from cooling problems, starting on March 15, 2011. Since then, multiple explosions and fires, especially related to spent fuel ponds, have been observed. Only with more precise information on the source, including fuel loadings, burn-up of fuel in the reactor, location and age of spent fuel, and nature of fires observed at the plants, can one model the range of possible release of fission products, and then determining the distribution of these products downwind due to wind, deposition from rain, etc. Assuredly, the best experts in Japan are engaged in exactly this task. Although generic calculations for release from reactors under a variety of breaches of reactor vessel and containment exist[29], and similar analyses have been done for spent fuel ponds[30], the actual releases in the cases at hand in Japan are specific to the exact conditions and nature of the accidents, and we can say little at this stage except to note that the Japanese authorities have ordered the evacuation of the areas surrounding the plant for up to 30 kilometers, and ordered residents to stay inside for the next 30 kilometers (Figure 4).

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[28]Yukiko Kumano, "Integrity Inspection of Dry Storage Casks and Spent Fuels at Fukushima Daiichi Nuclear Power Station," Tokyo Electric Power Company, 16 November 2010

[29]American Physical Society, *Report to The American Physical Society of the Study Group on Radionuclide Release from Severe Accidents at Nuclear Power Plants*, Rev. Mod. Phys. Volume 57, Issue 3, pp. S1–S144, 1985, at: <http://rmp.aps.org/abstract/RMP/v57/i3/pS1_1>

[30]See G. Thompson, "Robust Storage of Spent Nuclear Fuel: A Neglected Issue of Homeland Security," Institute for Resource and Security Studies, January 2003, section 4.3, p. 48 et passim, which provides an indicative estimate of the release of cesium 137 at a reactor spent fuel pond in the United States, at: http://www.irss-usa.org/pages/documents/CANReport.pdf

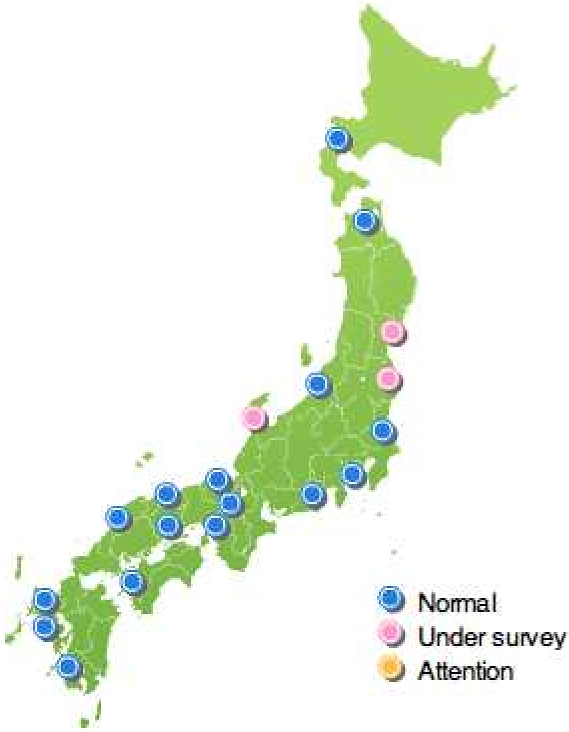
Figure 13: Areas for Fukushima Daiichi and Daini nuclear stations
Areas for required evacuation[31]

Enhanced radiation relative to natural background levels, at still relatively very low levels with respect to risk to individuals and whole populations, have been measured in major cities in Japan, as well as by the US Navy offshore. At time of writing (March 17, 2011), there are no publicly accessible, organized sources of radiation levels in Japan, only scattered reports.

[31]Source: Areas for Fukushima Daiichi and Daini nuclear stations

Areas for required evacuation, おしょー (Osho), Google Maps, 16 March 2011, [retrieved 18 March 2011]
<http://maps.google.com/maps/ms?ie=UTF8&hl=en&msa=0&msid=216386949281368528973.00049ea1ead8ecd245e94>

Figure 14: Disaster Prevention and Nuclear Safety Network[32]



Latest updated time 2011/03/17

Radiation Maximum Data List

Prefecture	Maximum
Hokkaido	29nGy/h
Aomori	30nGy/h
Miyagi	Under survey
Fukushima	Under survey
Ibaraki	867nGy/h
Kanagawa	72nGy/h
Niigata	41nGy/h
Ishikawa	Under survey
Fukui/Kyoto	77nGy/h
Shizuoka	81nGy/h
Osaka	58nGy/h
Okayama/Tottor	40nGy/h
Shimane	43nGy/h
Ehime	25nGy/h
Saga/Nagasaki	33nGy/h
Kagoshima	44nGy/h

The above table is a list of the maximum values of the space dose rate distributions shown from local governments in the latest updated date and time.

The national real-time radiation data system for Japan (see Figure 14) shows the radiation readings from the network of sensor sites across Japan, but those for the three most affected prefectures show "under survey." It is difficult to know if this is simply governmental control of possibly alarming data, or if the sensor system in these provinces is so degraded by the earthquake and tsunami to be off-line. In contrast, some prefectural web sites are providing some real-time data that might inform experts or the public.[33] It is not clear if updated maps

[32]Source: "Disaster Prevention and Nuclear Safety Network for Nuclear Environment," Nuclear Safety Division, Ministry of Education, Culture, Sports, Science and Technology, 17 March 2011, [retrieved 17 March 2011]
<http://www.bousai.ne.jp>
Note: A gray or Gy is a derived metric (SI) measurement unit of absorbed radiation dose of ionizing radiation; a nanogray is 1 billionth 10-9Gy. Units in this table are nanograys per hour. Realtime radiation data collected via the System for Prediction of Environment Emergency Dose Information (SPEEDI).
[33]See for example, http://www.atom-moc.pref.fukushima.jp/dynamic/C0012-PC.html; and http://houshasen-pref-ibaraki-mirror.cloudapp.net/present/result01.html

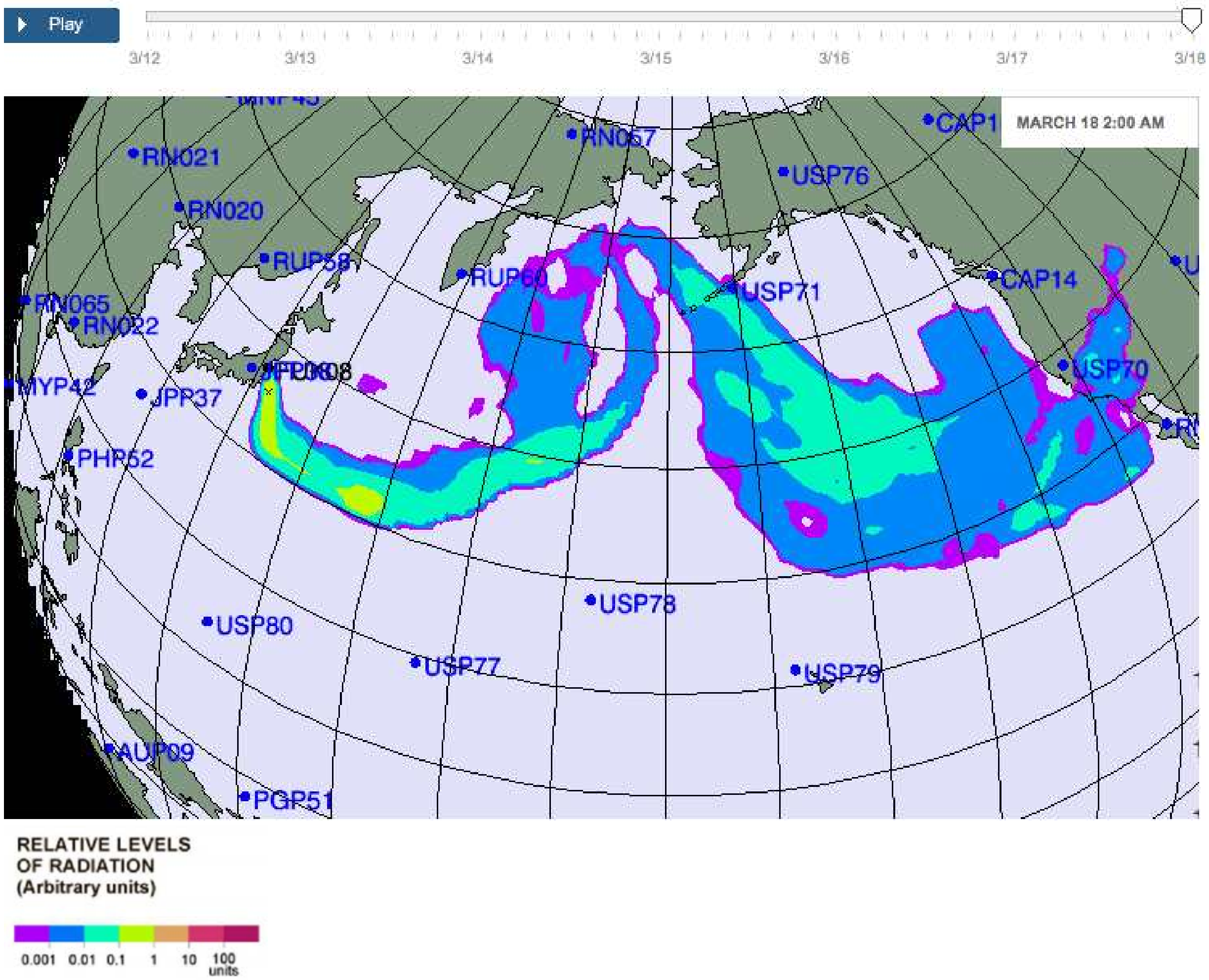
have been published in Japanese showing the spatial distribution of measured radiation since March 15 in Japan. Many Japanese are making their own decisions, and are starting to evacuate where possible, following the early decisions by some companies and countries to evacuate non-essential staff from cities downwind from the Fukushima plants.

Our impression from monitoring NHK and other media sources is that the government is controlling information on radiation levels and releases carefully to maintain public order and calm. Specifically, the government spokesmen for the most part have provided a great deal of information about events that have occurred already, especially in relation to plant failures and explosions. Much less information has been provided looking forward, possibly due to the unknowns that could render forecasts meaningless and inadvertently mislead the population.

However, in a modern, networked society, much experience with disaster response shows that individuals are capable of making intelligent decisions provided information is available to support these decisions, and that transparency is the best way to nurture emergent properties of social behavior that lead to constructive and cooperative outcomes. Given the public distrust that has developed in relation to the nuclear industry, and given the high level of public awareness of radiation affects due to the enduring, multigenerational effects of the nuclear explosions at Hiroshima and Nagasaki, combined with the high levels of community sensitivity to pollution from industrial plants in the decades since the Minamata disease was uncovered, it behooves the government to admit that while the current situation is increasingly stable, a runaway series of concatenating events could lead to a very large radiological release from Fukushima in a worst case scenario.

Japan also has an international responsibility to share this data in a timely manner, not least because countries downwind from Japan are vulnerable to the effects of low-level radiation, both via direct exposure, and via food chain accumulation. The Comprehensive Test Ban Treaty Organization has already produced a plume pathway (see Figure 15) although note that radiation levels are increasingly diluted as radiation is transported by wind around the northern hemisphere.

Figure 15: Forecast plume, March 12 - 18, 2011[34]



3. Implications of the reactor damage for the electricity system

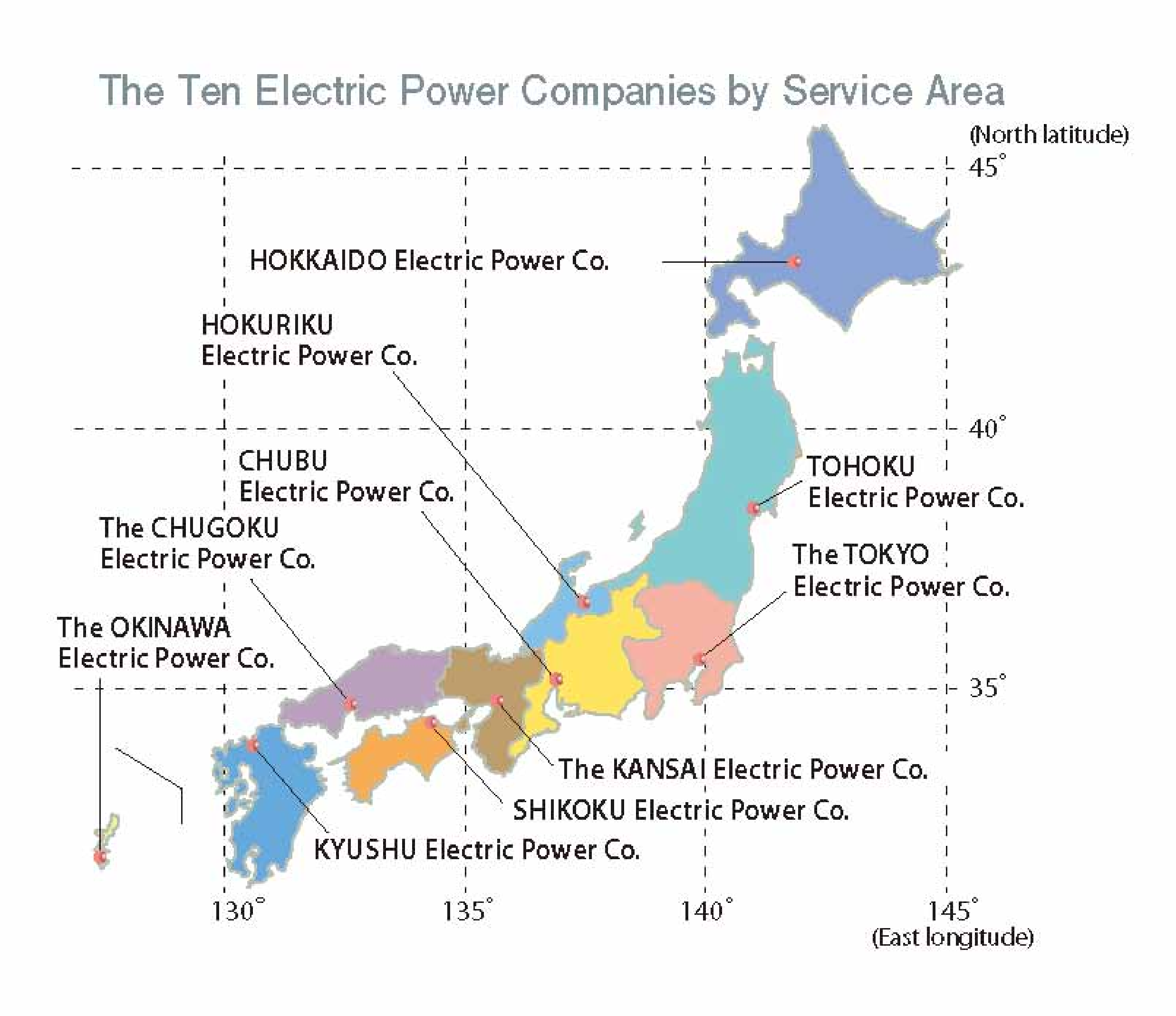
Power Requirements on the TEPCO and Tohoku Electric Power Company Systems

The earthquake-affected TEPCO and Tohoku Electric Power Company (Tohoku) systems which together serve the northern part of the Island of Honshu. As shown in Figure 16[35] Tohoku

[34]Source: Comprehensive Nuclear Test Ban Treaty Organization, [retrieved 17 March 2011] <http://www.nytimes.com/interactive/2011/03/16/science/plume-graphic.html?ref=science>

serves the portion of Honshu north of about 37° N latitude, with TEPCO serving the consumers located approximately south of 37° N latitude and east of 138° E longitude.

Figure 16: Japanese power companies



In 2009, TEPCO's sales to its customers totaled about 280 terawatt hours (TWh, or billion kilowatt-hours), and TEPCO plants generated just over 300 terawatt hours, about 30 percent of

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[35]From Federation of Electric Power Companies of Japan (FEPC) website: <http://www.fepc.or.jp/english/energy_electricity/company_structure/sw_index_01/index.html, visited 3/16/2011>.

which was by nuclear plants[36]. Tohoku sales in 2010 totaled about 79 TWh[37]. Tohoku sales in 2009 were about the same, and in that year the Company's generation and net power purchases totaled about 87 TWh[38] . These levels of generation and purchased power correspond to average power requirements over a year of 34,000 MW and 9,900 MW for TEPCO and Tohoku, respectively. TEPCO's peak power demand in 2009 was about 52,000 MW, and Tohoku's 2010 peak was about 14,500 MW. Based on recent news reports in Japan TEPCO expected that its peak power demand in the days immediately following the earthquake (not including the impacts of electricity rationing) would be 41,000 MW.

Existing and Operable TEPCO and Tohoku Supply-side Resources

Prior to the earthquake, TEPCO and Tohoku had a total of about 84,000 MW of supply-side resources to draw upon (21,250 for Tohoku as of 2009, and 62,700 for TEPCO), of which 10,600 MW were pumped-storage hydroelectric facilities used to store energy and provide peaking power. Table 4 provides a listing of most of the power plants in the two utility areas, but excludes purchased power and several smaller thermal power plants. As noted in Section 2, above, a number of nuclear and thermal (fossil-fueled) power plants were taken off-line as a result of the earthquake, and of those, the Fukushima I units are likely to be off-line indefinitely, if not permanently. 7150 MW of thermal generating capacity on the TEPCO system was taken off line following the earthquake. At least 350 MW of that capacity has since been restored. In addition, the Tohoku thermal power plants at Souma and Haramachi (totaling 4000 MW of capacity) are apparently heavily damaged, due to flooding and equipment damage, and may take 6 months or so to bring back on line. The newer Sendai thermal power plant unit 4 (446 MW) suffered flooding, as did the 950 MW Shin-Sendai thermal plant, which was evacuated due to a fire at the nearby oil refinery. Damage to transformer, transmission, and distribution facilities on the Tohoku grid occurred as well.

[36]Tokyo Electric Power Company, "Annual Report 2010," available as <http://www.tepco.co.jp/en/corpinfo/ir/tool/annual/pdf/ar2010-e.pdf>.

[37]Tohoku Electric Power Company, "Annual Report 2010." Available as< http://www.tohoku-epco.co.jp/ir/report/pdf/ar2010.pdf>.

[38]Tohoku Electric Power Co., Inc. "FACTBOOK," 2010,< http://www.tohoku-epco.co.jp/ir/fact-e.htm>.

Table 4: Power Plants in the TEPCO and Tohoku Service Areas[39]

SUMMARY OF TEPCO/Tohoku Capacity Data

D. von Hippel, 3/16/11

Energy Source	Name of Plant or Type	Unit Number	Company	Installed Capacity (MW)	Type of Reactor** or Fuel	Start Date (Year/Month)
Nuclear	Higashi-Dori	1	Tohoku	1,100	BWR	2005.12
Nuclear	Onagawa	1	Tohoku	524	BWR	1984.6
		2		825	BWR	1995.7
		3		825	BWR	2002.1
Nuclear	Fukushima Daiichi	1	TEPCO	460	BWR	1971.3
		2		784	BWR	1974.7
		3		784	BWR	1976.3
		4		784	BWR	1978.1
		5		784	BWR	1978.4
		6		1,100	BWR	1979.1
Nuclear	Fukushima Daini	1	TEPCO	1,100	BWR	1982.4
		2		1,100	BWR	1984.2
		3		1,100	BWR	1985.6
		4		1,100	BWR	1987.8
Nuclear	Kashiwazaki Kariwa	1	TEPCO	1,100	BWR	1985.9
		2		1,100	BWR	1990.9
		3		1,100	BWR	1993.8
		4		1,100	BWR	1994.8
		5		1,100	BWR	1990.4
		6		1,356	ABWR	1996.11
		7		1,356	ABWR	1997.7
Tokai		2		1,100	BWR	1978.11
TOTAL NUCLEAR				**20,582**		
Hydro	Pumped-storage (total)		TEPCO	6,808		
Hydro	Shinanogawa		TEPCO	177		
Hydro	Pumped-storage (total)		Tohoku	460		
Hydro	Pumped-storage (total)		EPDC*	3,275		
Hydro	Other		EPDC*	1,132		
TOTAL PUMPED-STORAGE HYDRO				**10,543**		
TOTAL OTHER HYDRO				**1,309**		
Thermal	Higashi Niigata		Tohoku	4,600	LNG, other Gas	
Thermal	Haramachi		Tohoku	2,000		
Thermal	Noshio		Tohoku	1,300	Coal	
Thermal	Akita		Tohoku	1,300	Crude, Fuel Oil	
Thermal	Futtsu		TEPCO	4.534	LNG	
Thermal	Kashima		TEPCO	4,400	Crude, Fuel Oil	
Thermal	Hirono		TEPCO	3,800	Crude, Fuel Oil, Coal	
Thermal	Sodegaura		TEPCO	3,600	LNG	
Thermal	Anegasaki		TEPCO	3,600	Crude, Fuel Oil, LNG, LPG, NGL	
Thermal	Yokohama		TEPCO	3,325	Crude, Fuel Oil, LNG, NGL	
Thermal	Chiba		TEPCO	2,880	LNG	
Thermal	Yokosuka		TEPCO	2,274	Crude, Fuel Oil, other Gas, Diesel Oil	
Thermal	Higashi Ogishima		TEPCO	2,000	LNG	
Thermal	Goi		TEPCO	1,886	LNG	
Thermal	Kawasaki		TEPCO	1,500	LNG	
Thermal	Minami Yokohama		TEPCO	1,150	LNG	
Thermal	Shinagawa		TEPCO	1,140	LNG	
Thermal	Ohi		TEPCO	1,050	Crude	
Thermal	Hitachinaka		TEPCO	1,000	Coal	
TOTAL THERMAL				**42,810**		
Renewable	Hachijo-jima		TEPCO	0.5	Wind	
Renewable	Hachijo-jima		TEPCO	3.5	Geothermal	
Renewable	(Five Units at Four Sites)		Tohoku	243.8	Geothermal	
Renewable	Other		Tohoku	16.2	Total of other non-hydro renewable	
TOTAL NON-HYDRO RENEWABLE				**264**		
TOTAL ALL GENERATION				**75,508**		
TOTAL ALL GENERATION LESS PUMPED-STORAGE				**64,965**		

*Plants owned by EPDC (Electric Power Development Co., LTD.) but in the TEPCO or Tohoku service territories

** BWR - Boiling Water Reactor, ABWR = Advanced Boiling Water Reactor, LNG = Liquefied Natural Gas, NGL = Natural Gas Liquids, LPG = Liquefied Petroleum Gas.

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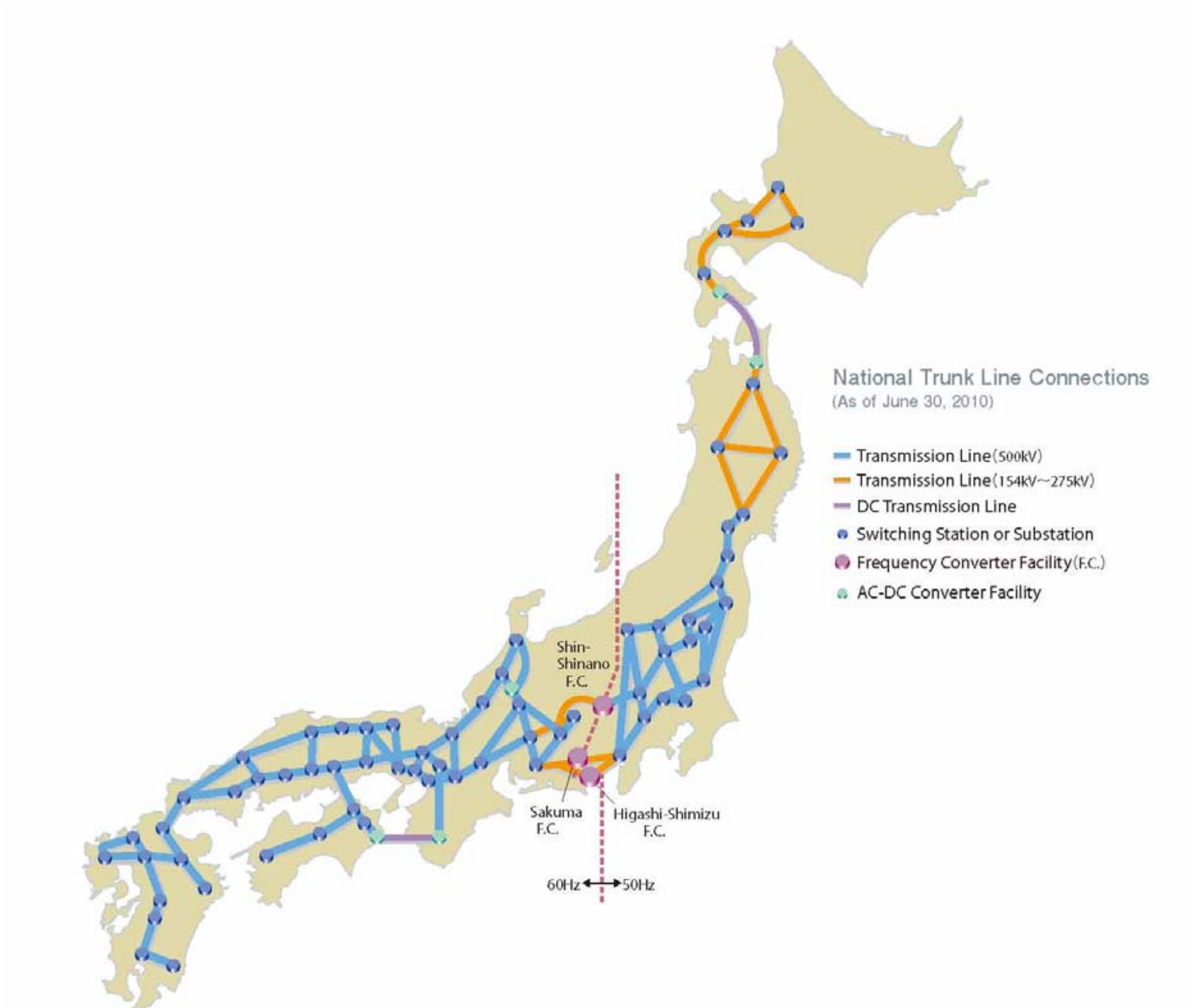
[39]Sources: Federation of Electric Power Companies of Japan, http://www.fepc.or.jp/english/energy_electricity/location/thermal/index.html and similar, visited 3/16/2011. Some data from Tokyo Electric Power Company, "Annual Report 2010," available as http://www.tepco.co.jp/en/corpinfo/ir/tool/annual/pdf/ar2010-e.pdf.
and Tohoku Electric Power Co., Inc. "FACTBOOK," 2010, http://www.tohoku-epco.co.jp/ir/fact-e.htm.

Some existing fossil-fueled generation capacity that had been “mothballed” (not used, but available to be restarted) may have already been restarted by TEPCO, and some more may be available.

Japan uses two electric power systems of two different frequencies. TEPCO, Tohoku, and utilities to the north use power at a frequency of 60 Hz, while other Japanese utilities generate and distribute 50 Hz power. The two systems are tied together through three frequency inverter stations, as shown in Figure 16, but the net result is that without the addition of more converter stations and transmission facilities, the capacity of TEPCO and Tohoku to import power from other big systems is limited, apparently to about 1000 MW. Building additional fossil-fueled capacity--the fastest would be gas-fired combined cycle plants fueled with relatively expensive, imported liquefied natural gas--would take two or more years, even with the most aggressive of programs. New coal-fired power plants will probably take a minimum of three to five years to build.

Figure 17: Transmission Lines and Interconnections[40]



The net result of the supply outages caused by the earthquake, tsunami, and subsequent problems at nuclear and thermal power plants, plus constraints on power imports and short-term additions of new plants, means that the TEPCO and Tohoku service territories may be in short supply situations for some time.

Demand-side Resources for Power Companies Affected

Both TEPCO and Tohoku have announced power rationing programs, consisting of rolling blackouts in many areas, but exempting some regions, including earthquake-affected zones and

[40]Source: Federation of Electric Power Companies of Japan (FEPC), <http://www.fepc.or.jp/english/energy_electricity/company_structure/sw_index_02/index.html, visited 3/16/2011>.

central Tokyo[41]. With a considerable portion of their generation capacity unavailable in the short-term, and three or more reactors-worth of power now gone for good, the power companies in Eastern Japan serving the areas affected by the earthquake and tsunami will be scrambling to provide electricity to their consumers. Both companies have announced power rationing. In the Tokyo Electric Power (TEPCO) area, demand management by rotating curtailments seem so far not to have been as extensive as originally expected, probably due to the fact that a lot of businesses and industries have yet to reopen following the earthquake, and that millions of consumers have lost power (and in the areas suffering most from the tsunami, sadly, the infrastructure to use it) due to breaks in the power transmission and distribution system.

In addition, the summer months, when electricity needs tend to peak in Japan, are still approaching. Though as noted above, it may be that the lack of generation capacity will spur TEPCO and other affected companies, and their customers, to more aggressively pursue energy efficiency measures and generation of power on-site by consumers (or distributed generation) through the use of both renewable resources (such as solar PV, and solar hot water, which have the advantage of being largely coincident with peak summer power demand) or fossil resources (natural gas-fired units, for example). The high price of electricity in Japan—which seems likely to ultimately go higher as a result of this incident—serves as an additional incentive to reduce electricity demand as much as possible. Although Japan over the past several decades has been among the world's leaders in energy efficiency, efficiency improvements have stagnated somewhat in recent years. A recent report by the International Energy Agency included a number of suggestions as to how Japan could achieve even greater energy savings with more aggressive policies[42].

Medium-term Implications for TEPCO and Tohoku Service Areas

Even if the reactor cores and spent fuel pools in the affected nuclear power plants are stabilized immediately, a number of questions remain, the answers to which will determine what the electricity supply system in Japan looks like for years to come. For example, how many reactors affected by the earthquake will ultimately pass inspection and be able to be restarted? Will analysis of the results of the earthquake uncover generic problems that may cause other reactors, even those not affected by the earthquake, to need to be shut down, in Japan and elsewhere?

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[41]"See, for example Tohoku Joins Tepco in Rationing Power", *Japan Times*, March 16, 2010, [retrieved 17 March 2011] <http://search.japantimes.co.jp/cgi-bin/nn20110316a5.htm>.

[42]International Energy Agency, "Progress with Implementing Energy Efficiency Policies in the G8." Dated July, 2009, and available as www.iea.org/G8/docs/Efficiency_progress_g8july09.pdf.

On the demand side, what fraction of the industrial, commercial, and residential infrastructure that was affected by the earthquake will be rebuilt, as opposed to moving elsewhere? At what level of energy efficiency will infrastructure be rebuilt? Depending on how these uncertainties play out, the earthquake-affected area of Japan could be short of electricity for many years.

It seems clear, however, that the three affected Fukushima I reactors will not be reparable, and it may well be, given the explosion at Fukushima I unit 4, that a combination of damage and radioactive contamination at units 4 through 6 will render those units un-repairable as well. Thus units 1 through 3, and maybe the entire Fukushima I complex, will need to be "decommissioned" — dismantled, decontaminated and safely disposed of—at a cost that will run into the tens of billions of dollars.

It is possible that other nuclear plants—a total of seven TEPCO, four Tohoku, and one Japan Atomic Power (the 1100 MW Tokai unit 2) nuclear reactor units, as well as a number of coal- and gas-fired plants that went off-line following the earthquake — will also be affected, and be either un-repairable or require lengthy repairs.

In order to provide electricity to their customers during this period, TEPCO and Tohoku will need to use their existing fossil fuel plants much more heavily, probably for many years, than they would have had they been able to use the nuclear plants. In addition to incurring extra costs for purchase of fossil fuels, this will result in emissions of probably tens of millions of tonnes of additional emissions of greenhouse gases and other pollutants, although the extent of these additional emissions, so far as we know, has yet to be estimated (beyond the extremely preliminary estimates we provide below).

4. Scenarios for the evolution of the TEPCO and Tohoku Electric Power Company systems in the coming years

As is clear from the description of the status of the TEPCO and Tohoku Electric Power Company electrical systems provided above, providing electricity to a recovering regional economy in the coming years, working without the generation resources destroyed or disabled by the earthquake, tsunami, and nuclear accident, will be daunting. How those electricity supplies are restored, and at what pace, will have a profound impact on the lives and livelihoods of the people in the affected areas and beyond. Below we outline several possible "scenarios" of recovery of the electricity system. In these early days, it is impossible to explore these scenarios in quantitative or even qualitative detail. Rather, we have tried to provide a set of questions and issues for further exploration as the nuclear crisis unfolds, and as the parameters of the required electricity system recovery become more evident. We should note that all of these scenarios assume implicitly that the ongoing problems with the troubled reactors and spent fuel pools at Fukushima I are ultimately addressed such that impacts do not reach the “Chernobyl level”. That is, we assume that the TEPCO/Tohoku areas are not, when the situation is resolved, subjected to radioactive fallout sufficient to make substantial areas unlivable.

“Best Case” Scenario

Based on what we are seeing today, (March 17th, 2011), the combination of structural damage and radioactive contamination make it unlikely that any of the Fukushima I nuclear plants will ever be restarted. Units 1 through 6 will need to be decontaminated and decommissioned, a process that will be lengthy (years, perhaps a decade or more), expensive (billions of dollars), and also difficult to the point of requiring the importing of experts with experience in recovering from the U.S. Three Mile Island and Soviet Chernobyl incidents. It is likely that new technologies and methods will need to be developed to deal with the problems that the cleanup will pose. Japanese policies toward movement and storage of spent fuel may need to change as well, in order to deal with the considerable quantities of spent fuel on the site (assuming they remain intact, and even more so if they are physically compromised) that at present have nowhere to go.

Beyond Fukushima I, a Best Case might allow the currently off-line Onagawa nuclear plant (Tohoku) back on line soon, perhaps before the period of summer peak demand. It is at present unclear what damage the Fukushima II plants may have sustained, though they appear to have been shut down successfully, albeit with some difficulty. It seems likely that the Fukushima II plants will require a fairly lengthy inspection and some repairs before they are restarted (assuming the inspection turns up no major problems). Even at that, public concern may be a factor in keeping the Fukushima II plants offline longer. A Best Case might have these plants back on line in two years. The Higashidori and Tokai plants will require similar structural assessments and repairs, and might take a year or more to be brought back on line. Further, three units (totaling 3300 MW) of the Kashiwazaki-Kariwa nuclear plant, which was affected by a 2007 earthquake, are currently undergoing inspection and evaluation for earthquake resistance, possibly continuing through April.[43]

The joint thermal power plants at Souma (Soma) and Haramachi (together 4000 MW) are heavily damaged, and might take six months or so to be restarted under a Best Case scenario (Figures 18 and 19).The status of the approximately 7000 MW of TEPCO’s thermal power

[43] “Status of the Inspection and Restoration Works Performed after the Niigata-Chuetsu-Oki Earthquake” (as of March 10), Press Release , Tokyo Electric Power Company, 10 March 2011 [accessed 18 March 2011] <http://www.tepco.co.jp/en/press/corp-com/release/11031001-e.html>

plants that were placed offline at the time of the earthquake is at present unclear, but we assume in this Best Case that the TEPCO thermal plants can be brought back on line relatively quickly.[44]

Figure 18: Damage at thermal power plant, Haramachi, in South-Soma (Fukushima prefecture)[45]

[44]On 17 March, a TEPCO vice president said its priority is to get the Kashima thermal power station (4400 MW) back on line as soon as possible, but provided no estimate of the time required. He raised the possibility of using several 300MW emergency power generators attached to telecom companies, but the possibility seemed slim.

「鹿島火力発電所の復旧急ぐ」東電副社長 , 日本経済新聞, 17 March 2011, [retrieved 18 March 2011]
<http://www.nikkei.com/news/latest/article/g=96958A9C93819696E3E5E296E08DE3E5E2E1E0E2E3E3E2E2E2E2E2E2>

[45]東北地方太平洋沖地震に伴う東北電力の電力設備被害状況写真, Tohoku Electric Power Company, 13 March 2011, [retrieved 18 March 2011]
<http://www.tohoku-epco.co.jp/emergency/9/1182292_1807.html>

Figure 19: Damage to transmission lines, Otsuchi, Iwate prefecture[46]

In a Best Case scenario, then, about 4700 MW of nuclear generating capacity is gone, and must be replaced or otherwise compensated for by supply- or demand-side resources. Further, 2700 MW of capacity that were to be completed at Fukushima I during the next decade seem highly unlikely to be so, and the generation that would have come from those units will need to be replaced or compensated for as well. Another 6600 MW of nuclear capacity is likely to be offline for one to three years, 3300 MW at the Kashiwazaki-Kariwa plant is offline for inspection, and 4000 MW of thermal capacity seem likely to be offline through the summer. On March 17 a TEPCO vice-president said that full operation of the Kashiwazaki-Kariwa NPP will be difficult, due to emotion about nuclear power.[47] TEPCO's total generation in 2009 was about

[46] 東北地方太平洋沖地震に伴う東北電力の電力設備被害状況写真, Tohoku Electric Power Company, 13 March 2011, [retrieved 18 March 2011] <http://www.tohoku-epco.co.jp/emergency/9/1182292_1807.html>

[47] 「鹿島火力発電所の復旧急ぐ」東電副社長 , 日本経済新聞, 17 March 2011, [retrieved 18 march 2011]

300 TWh, of which nearly one-third was from nuclear power. [48] This fraction itself is down from the 38% of TEPCO generation nuclear power supplied in 2006, before the 2007 Niigataken Chuetsu-Oki earthquake.[49]

Our analysis of this "Best Case" scenario is necessarily preliminary and incomplete, but for the TEPCO service area, some of the implications appear to be as follows. The annual output of remaining operating nuclear units totals 4912 MW (this is the TEPCO nuclear capacity as of 3/17/11 that was not affected by the earthquake and subsequent events). At a 90% capacity factor, which is probably higher than would be expected in the coming year under the circumstances, the output of these reactors would be about 39 TWh/yr. As nuclear generation accounted for about 90 TWh in 2009, this implies that if demand is the about same in the coming year as it was in 2009 (though, given the impacts of the earthquake on infrastructure, the economy, and the consumption patterns of Tokyo-area residents, lower consumption is definitely possible) then an additional 51 TWh would have to be generated by fossil fuel plants that was not in 2009. At an average emission factor of 0.6 tonnes CO_2/MWh (roughly reflecting TEPCO's generation mix of mostly oil- and gas-fired thermal power plants) this implies annual additional CO_2 emissions of about 31 million tonnes. Given that TEPCO's hydroelectric generating capacity is virtually all (all but a few percent) "pumped-storage" hydro, that is, hydroelectric capacity built to provide peaking power for the system by storing baseload (night-time) coal-fired and nuclear generation by pumping water uphill to store energy, virtually all non-nuclear generation will be fossil-fueled. If demand in 2011 is similar to 2009 levels, TEPCO's thermal plants would be called upon to produce about 260 TWh of output in 2011, which implies an impossible capacity factor of an nearly 100% for the thermal power plants available now, and a still-very-high 81% if the all of the thermal power plants that were shut down during the earthquake are restarted quickly. Either way, this is a significant increase from the 65% average capacity factor experienced for thermal plants in 2009. We do not know whether all of the thermal plants on the TEPCO system can sustain significantly higher capacity

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<http://www.nikkei.com/news/latest/article/g=96958A9C93819696E3E5E296E08DE3E5E2E1E0E2E3E3E2E2E2E2E2E2>

[48]Tokyo Electric Power Company, "Annual Report 2010," [retrieved 17 March 2011] <http://www.tepco.co.jp/en/corpinfo/ir/tool/annual/pdf/ar2010-e.pdf.

[49] "State of the Power Station After the 2007 Niigata-Chuetsu-Oki Earthquake", Tokyo Electric Power Company [retrieved 18 March 2011] <http://www.tepco.co.jp/en/niigata/plant/index-e.html>; Akira Fukushima, "Report on the Earthquake Impact to Kashiwazaki-Kariwa NPP," Nuclear and Industrial Safety Agency, September 20, 2007; Seismic Safety Expert Mission, IAEA, "2nd Follow-Up IAEA Mission in Relation to the Findings and Lessons Learned from the 16 July 2007 Earthquake At Kashiwazaki-Kariwa NPP, 'The Niigata-ken Chuetsu-Oki Earthquake'", Tokyo and Kashiwazaki-Kariwa NPP, Japan, 1-5 December 2008.

factors, or whether sufficient fuel will be available—that is, whether the operable delivery and storage capacity for the needed additional gas, oil and coal—is sufficient to provide the needed level of thermal generation.

Viewed from the perspective of peak demand, the short-term situation is even more constrained. TEPCO's peak demand in 2009 was about 52 GW. This is a few GW greater than the total capacity of all of the thermal plants on the TEPCO system (assuming that all are available, including those shut down during the earthquake) plus the available remaining nuclear units, plus all of the pumped-storage hydro capacity. This implies that a combination of peak demand reduction measures, coupled with electricity demand reduction related to earthquake damage to infrastructure and the economy, will be required to get the TEPCO system through the next few years, even in this "Best Case" scenario.

We have not yet done the same preliminary analyses of scenarios (either "Best Case" or the two cases that follow) for the smaller (roughly 80 TWh in annual sales, and roughly 14 GW of peak load[50]) Tohoku electricity system, but we would expect to find results that are qualitatively similar to our estimates for the TEPCO system.

In the Best Case scenario, assuming no significant damage is found in the review of the other nuclear and thermal plants that have been shut down, when those plants are restarted, in perhaps one to three years, much or all of the short-term electricity supply shortage in the area may be eliminated, especially, if new fossil-fueled plants (such combined-cycle natural gas plants, which can be built in a few years if gas supplies are adequate) are built starting very soon.

"Base Case" Scenario

As a Base Case scenario for the near- and medium-term evolution of the power systems of the TEPCO and Tohoku service areas, we could see the conditions for the nuclear reactors described in the Best Case holding with the exception that the nuclear plants (other than Fukushima I) in the earthquake-affected area will undergo more lengthy inspection, and/or inspections turn up problems that must be addressed, and/or local political opposition delays restarting the plants. Inspections at some thermal plants also turn up problems that mean that they are out of service longer, or need to be replaced. In this case, the supply shortfall for the two companies is likely to last longer, perhaps several years longer (around five years total), and would need to be ameliorated by a combination of much more thermal generation, construction of new thermal generation plants (assuming availability of fuel), and probably a significant effort to curb net

[50] Tohoku Electric Power Company, "Annual Report 2010," [retrieved 15 March 2011] <http://www.tohoku-epco.co.jp/ir/report/pdf/ar2010.pdf>

demand for both electrical energy and peak power. Curbing demand could take the form of rotating power cuts, agreements with industry to curtail consumption at peak times (or, in fact, to move elsewhere, as unappealing as that is for the local economy), aggressive energy efficiency programs (which would have the added benefit of reducing fuel requirements and costs), and/or encouraging residents, businesses, and industries to develop on-site generation, including solar photovoltaic (PV) generation, and gas-fired combined heat and power systems. Though northern Japan is not ideally suited to solar power production, solar PV generation offers an advantage that it will provide the most power in times of peak summer electricity demand in Japan, helping to reduce the summer peak that central electricity generating stations will need to handle.

"Worst Case" Scenario

We postulate that a "Worst Case" scenario would extend the Base Case in that all of the nuclear power plants in the earthquake area are found to have significant seismic or other damage, leading to prolonged (more than 5 years) retrofit requirements, and some thermal plants are found to have been compromised to the point where they cannot be repaired, and must be replaced (requiring several years). In addition, the results of inspections at the earthquake-affected power plants, coupled with nationwide public concern about the safety of nuclear plants, causes other nuclear plants (apart from the earthquake-affected plants) in the TEPCO/Tohoku service areas and maybe elsewhere in Japan to be taken off line on a rotating basis for damage assessment and/or earthquake retrofit. These additional conditions would likely result in the need for many more new thermal plants (and related fuel supplies), and an even higher reliance on demand-side measures (including power rationing) than in the Base Case to balance available supply and demand over probably five to ten years.

Next Steps

As noted above, we consider these Scenarios no more than an initial range of possible outcomes. Much more detailed consideration of the parameters and results of each of the scenarios, including, the greenhouse gas and other pollutant emissions consequences of make-up power production, the level of unserved demand over the years and the impact of unserved demand on the economy, the implications of the scenarios for future nuclear development in Japan (and, indeed, elsewhere as well), the potential impact of a strenuous energy efficiency/renewable energy effort in reducing the amount of unserved demand, and the implied costs for different scenarios.

In particular, Japan may wish to examine carefully the costs of establishing a nationally integrated "smart grid" that enables intermittent renewables to be scaled up alongside a massive program of fast, super-efficient end use efficiency in all sectors. This approach may be cheaper, faster, and more resilient in the short and the long-run than relying on coastal coal and nuclear-fired power plants to make up for the immediate and long-term shortfalls in generating capacity.

5. Implications of Incident for Future East Asian Use of Nuclear Power

The incidents at the Fukushima plants, in our view, are highly likely to have a chilling effect on the perception of nuclear power in many countries, just as the earlier accidents at Three Mile Island in the United States and at Chernobyl have had. Politicians and the public, particularly in countries like Japan, Taiwan, and South Korea, who have been looking to expand their nuclear fleets, as well as in North America and Europe, will be asking for additional certainty regarding the safety of nuclear power, with the likely result being at least delays in deployment of additional reactors, more rigorous safety studies for existing and to-be-built reactors, and possibly additional costs for safety modifications and as a result, construction delays. Additional costs are a key concern for nuclear power plants, because the costs of building nuclear plants are by far the largest component of the costs of power from nuclear. It also seems likely that the accident in Japan will cause some countries that do not yet have nuclear power, but are actively seeking it, to look more carefully at the technology and its implications. Indonesia, for example, has announced plans to develop nuclear power in recent years, and the re-starting of the nuclear power program in the Philippines has been discussed. Both countries have a recent history of volcanism and earthquakes, and Japan's experience may (and probably should) give them pause. In the East Asia region, however, by far the majority of new reactors planned as of today (or at least, as of last week), were to be installed in China. Will the events in Japan affect Chinese plans for nuclear development? Public involvement in decisions such as nuclear reactor deployment in China (and, for example, in Vietnam, another country with active plans to build reactors) has traditionally been much more limited than in the other nations and regions mentioned above, so it will be interesting to see how Chinese plans are affected by this event.

Ultimately, the additional scrutiny of nuclear power may lead to accelerated development and deployment of new reactor types that will be more robust under accident conditions. Indeed, the reactors being built today should be significantly more robust than the Fukushima I reactors, which are now 30 to over 40 years old. In the long term, safer reactors could be the result of the response to the accident at the Japanese plant, but it seems likely that additional development of nuclear power will be delayed in many countries as a result of this accident.

Regional responses

China

The Fukushima nuclear crisis has had an enormous impact on China. Given its geographical proximity to Japan and with a large Chinese population living and working in Japan, the Chinese government and a great many Chinese citizens have been keeping a close watch on the unfolding events.

On March 16th, the Chinese government held a high level State Council meeting to discuss the Japan nuclear crisis and to consider China's own nuclear planning. At the meeting, the government made three major decisions on nuclear power. Firstly, the government decided to halt its plan to build new nuclear power plants. Secondly, it ordered a re-examination of the safety risks of nuclear power stations currently under construction. Any safety faults discovered will lead to construction being stopped. Thirdly a decision was made to enhance the management of safety aspects of nuclear power stations currently in operation in China.

In a rare stand, the Chinese government indicated that the utmost priority should be attached to nuclear safety. China will also step up its process of drafting nuclear safety planning and adjust its middle and long term nuclear development plan. Any new nuclear plan will be shelved, including preliminary work.

Due to the fact that this is a nuclear crisis in Japan, Chinese media were allowed to report freely. Such a rare media freedom for coverage of nuclear issues offers a rare opportunity for Chinese media to introduce concerns over nuclear power and its related hazards and risks. Though some nuclear specialists, indeed most of them, are supportive of nuclear power, were invited to give comments on television programs; as a result, mounting concerns amongst the general public have emerged, largely making clear that they would rather not have nuclear power at all. Other scholars indicated this is a golden opportunity to popularize the issue and to increase knowledge amongst the public on nuclear radiation and safety measures.

The Chinese language newspaper Southern Metropolitan Daily also published a map outlining names and locations of all proposed Chinese nuclear plants, plants under construction, and those in operation. This is the first publicly released information on China's nuclear industry and planning. For the first time the Chinese public is able to know about many of these new nuclear plants and their locations. These revelations will surely generate a huge outcry and opposition from the public.

After the Deluge Short and Medium-term Impacts of the Reactor Damage Caused by the Japan Earthquake and Tsunami
Nautilus Institute for Security and Sustainability
March 17, 2011

When the media outlet such as television channels and other media allow public debate on the safety of nuclear power, a strong anti-nuclear force is in the making in China.

In Taiwan, Taiwan's Atomic Energy Council reportedly began internal discussions on establishing a mechanism with China for notification in case of nuclear accidents.[51]

Russia

While Russia is a major power in civil nuclear energy, there are very few reactors in the Russian Far East, and they are small. Following the earthquake, Russia announced offers of aid and expertise to Japan. President Medvedev announced that while all of the Sakhalin II LNG production is already spoken for, he "ordered all Sakhalin LNG cargoes to be diverted to Japan, even if other buyers are left out".[52]

The spectre of a catastrophic failure of containment of the Fukushima I reactors brings echoes of the antagonism between the two countries after the fall of the Soviet Union when Russia clandestinely dumped reactors and spent nuclear fuel from decommissioned Soviet navy submarines in the Sea of Japan off Vladivostok.[53]

South Korea

From the day of the earthquake and tsunami, President Lee Myung-bak of South Korea pledged support for Japan, including emergency supplies worth $12.5 mn. following a request from the

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[51] Lin Shu-yuan and Christie Chen, "Taiwan Mulling Nuclear Safety Mechanism with China," March 17, 2011, *CNA News Service*, at <http://focustaiwan.tw/ShowNews/WebNews_Detail.aspx?ID=201103170034&Type=aSOC>

[52] Isabel Gorst, "Russia: LNG Aid for Japan", *Financial Times FT Blog*, 14 March 2011, [accessed 18 March 2011] <http://blogs.ft.com/beyond-brics/2011/03/14/russia-lng-aid-for-japan/>

[53] Hajime Sasaki, "Japan's Assistance for the Dismantlement of the Decommissioned Nuclear Submarines and Related Project in the Russia Far East," Technical Secretariat of the Committee on Cooperation to assist the Destruction of Nuclear Weapons Reduced in the Russian Federation, Japan, IAEA, 21st CEG Plenary Meeting, 05-07 September 2007, Bruges, Belgium [retrieved 17 March 2011] <http://www.iaea.org/OurWork/ST/NE/NEFW/CEG/documents/plenary21_10E.pdf>; Jon Gauslaa, "The Pasko case", *Bellona*, 24 June 2005, [retrieved 18 March 2011] http://www.bellona.org/archives/newsarchive?filtervalue=2011> ; Richard Tanter, "The Humble Star of Hope: Environmental Heroes in the Shadow of War, 環境雑学マガジン、[Kankyô Zatsugaku Magazin], 138 (January 14, 2003), [retrieved 18 March 2011] <http://www.globalcollab.org/about/staff/richard-tanter/richard-papers/the-humble-star-of-hope-environmental-heroes-in-the-shadow-of-war/>

Japanese government. Lee also ordered renewed inspection of the safety of South Korea's 21 nuclear power plants, as well as a wider focus on "earthquake-proof conditions of public buildings, early warning systems and overall contingency plans".[54] On March 15th the monthly civil defence training, which usually aims at preparing for sudden attack from North Korea, instead focused on preparation for facing earthquake and tsunami disasters.

However, as the Fukushima nuclear crisis continued to unfold, President Lee struck an ill-timed note during a visit to the United Arab Emirates at a ground-breaking ceremony for the start of construction of four nuclear power plants to be built by Korean companies in a contract worth $18.6 bn. In December 2009 South Korea won the contract in the face of intense competition from French and Japanese companies. In a remark reported abroad with the headline "S. Korea boasts of safety of home-built nuke plants", Lee reassured his hosts that they would be receiving "top-class plants, and that "given the safety and effectiveness of Korea's nuclear technology, the Korean nuclear reactors will become a model in the Middle East".[55]

Domestically, the Japanese nuclear crisis provoked sharp division between the government and opposition political parties and civil society critics of South Korea's nuclear power system. The Ministry of Knowledge Economy acknowledged the potential impact of the crisis in Japan on South Korea's ambitious plan to increase the number of power plants from 21 at present to 38 by 2030, to supply 59% of the country's electricity. However, to reach that goal, 10 new reactors will be necessary, in addition to the seven under construction at present. Local groups in areas near candidate sites for these new nuclear facilities reacted sharply to the news from Japan. Opposition legislators called for reconsideration of the nuclear power building plan, and particularly called attention to the fact that Korean nuclear facilities are at present built only to resist an earthquake of 6.5 on the Richter scale.[56] The Ministry of Knowledge Economy,

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[54]Lee Chi-dong, "Lee Orders Close Safety Checks on S. Korea's Nuclear Facilities," *Yonhap News*, 16 March 2011, [retrieved 16 March 2011] <http://english.yonhapnews.co.kr/national/2011/03/16/96/0301000000AEN20110316009200315F.HTML>

[55]"S. Korea Boasts of Safety of Home-Built Nuke Plants", *AFP*, Nuclear Power Daily, 14 March 2011, [retrieved 16 March 2011] <http://www.nuclearpowerdaily.com/reports/S_Korea_boasts_of_safety_of_home-built_nuke_plants_999.html>

[56]Lee Ji-yoon, "Concerns Growing Over Korean Nuclear Power Plants", *Korea Herald,* 15 March 2011, [retrieved 16 March 2011] <http://www.koreaherald.com/national/Detail.jsp?newsMLId=20110315001074>

however, maintained that "opposition to nuclear power might arise, but there will be no change in South Korea's nuclear plans."[57]

North Korea

It is unclear, at this early stage, to what extent the nuclear crisis in Japan might affect North Korea's plans to move ahead with its planned program of domestic light-water reactor development.[58] It is possible that the accident in Japan will serve to encourage the North Korean leadership to accept international technical assistance on reactor safety, if such assistance is offered. It is also possible that South Korea and the United States may take a very hard line indeed against an attempt by the North to complete and turn on a small light water reactor that is upwind and would be of highly dubious quality and reliability.

On the other side of the equation, we would hope that the experience in Japan would help to induce the international community to offer such assistance to North Korea. North Korea delivered a message of condolence to the Japanese people through North Korean Red Cross (Rep. Jang Jaeyeon) to the representative of Japan Red Cross (Mr. Konoe).[59]

Southeast Asia

Alvin Chew at the S. Rajaratnam School of International Studies, Nanyang Technological University in Singapore articulated the combination of optimistic analysis and political determination common in the burgeoning nuclear establishment in Southeast Asia:

> "It is therefore assessed that most countries will proceed with the building of new nuclear plants. It is unfortunate that Japan resides on the 'Ring of Fire', but Tokyo is unlikely to be deterred from continuing with the operation of future nuclear power plants. However, we can anticipate an increase in domestic opposition to nuclear energy in Japan and elsewhere arising from the Fukushima incident. It is a risk that most nations have to

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[57]Lee Soon-hyuk, "Lee Administration Stays Course on 'Nuclear Renaissance'", *The Hankyoreh*, March 16, 2011, [retrieved 16 March 2011] <http://english.hani.co.kr/arti/english_edition/e_business/468327.html>

[58]See, for example, Siegfried S. Hecker (2010), "A Return Trip to North Korea's Yongbyon Nuclear Complex," *NAPSNet Special Report*, dated November 22, 2010, and available as <http://www.nautilus.org/publications/essays/napsnet/reports/a-return-trip-to-north-korea2019s-yongbyon-nuclear-complex>.

[59]Some South Korean media saw North Korea as using this opportunity to pursue normalisation of relations with Japan. See '북한 적십자, 日대지진 피해에 위로 전문' ("N.K North Korea Sent Condolence on the Earthquake Disaster in Japan"), *Chosun Ilbo*, March 15, 2011, [retrieved 16 March 2011] <http://news.chosun.com/site/data/html_dir/2011/03/14/2011031402254.html>

contend with. But certainly, with more than 400 nuclear reactors operating throughout the world, it is a testament that the advantages of nuclear energy outstrip any fears of a nuclear disaster."[60]

Malaysia

Malaysia has been proceeding quite rapidly over the past year towards its announced goal of establishing a nuclear power plant in that country, and the country's Deputy Prime Minister said that the Malaysian government was closely monitoring the Japanese situation, but would "implement what is the best" for the country. "In this matter, we have an agency that is responsible and they know what they are doing and we are confident that they will implement what is the best," said Yassin.[61] Others, including the second largest party in the ruling coalition government, the Malaysian Chinese Association, called for caution.[62] Environmental organisations, however, such as Sahabat Alam Malaysia (SAM) and the Consumers' Association of Penang (CAP) responded by arguing that "combining energy efficiency measures and renewable energy to meet our energy demand would eliminate any justification for nuclear power and mega dams."[63]

Indonesia

In Indonesia, Husi Hastow, the head of the National Nuclear Power Agency discounted the influence of the Japanese crisis on his agency's advocacy of a 4 x 1,000 MW nuclear power station.

> "He assured that the technology used in an Indonesian nuclear plant would be the most up to date, adding that a safe location played an important role in the plant's security. 'If we use state-of-the art technology but place it in a dangerous location, the facility will face the same risk as a less sophisticated one. We have to find a location that suits international requirements, including one that is safe from tsunamis and other natural elements,' he said.

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[60] Alvin Chew, "Japan Earthquake and Tsunami: End for the Nuclear Industry?" *RSIS Commentaries*, No. 42/2011, 16 March 2011, [retrieved 16 March 2011 <http://www.rsis.edu.sg/publications/Perspective/RSIS0422011.pdf>

[61] Asrul Hadi Abdullah Sani, "Malaysia Says to Go Ahead with Nuclear Plans, to Learn from Japan Crisis", *Malaysian Insider*, 15 March 2011, [retrieved 16 March 2011] <http://themalaysianinsider.com/malaysia/article/malaysia-says-to-go-ahead-with-nuclear-plans/>

[62] "Japan's Nuclear Crisis Casts Shadow on Malaysia's Nuclear Ambition", *Kyodo News*, 15 March 2011 [retrieved 16 March 2011 <http://english.kyodonews.jp/news/2011/03/78246.html>

[63] SM Mohamed Idris, "Stop Plans for Nuclear Power Stations, Mega Dams", *Malaysia Kini*, 15 March 2011, [retrieved 16 March 2011] <http://www.malaysiakini.com/letters/158692>

Meanwhile, a representative of BPMigas announced that the government anticipates an increased surge of demand for natural gas from Japan in the short-term. He indicated that "20 cargoes of LNG from the Bontang Plant in East Kalimantan were still available for sale. At present, Japan is one of the main buyers of LNG produced at the Bontang Plant."[64] In the extreme energy circumstances following the earthquake, Japan's substantial involvement in Indonesian gas production will mean that there will be heightened pressure on the Indonesian government to maintain its policy of emphasizing the export of gas, rather than allocating supplies to domestic electricity production.

Australia

Australian uranium plays a major role in the operations and planning of the Japanese nuclear power industry and TEPCO in particular. In 2009 Australia exported 9,706 tonnes of uranium oxide, equivalent to 8,230 tonnes of uranium, for a value of $1.1 bn. In the same year 2,500 tonnes of this uranium oxide was exported to Japan.[65] Until the recent events, Japanese reactors were predicted to require 8,195 tonnes of uranium in 2009, with Australia supplying about one-quarter of Japanese requirements from the Ranger and Olympic Dam mines.[66]

In early 2009, Tokyo Electric Power (TEPCO), together with Toshiba and the Japan Bank for International Cooperation (JBIC) formed a new company named Japan Uranium Management, which then acquired a 20% share of the Canadian-based mining company Uranium One, which owns the Honeymoon uranium mine in South Australia. At the time of the 20.2 billion yen purchase, TEPCO stated that, "concurrently, TEPCO, Toshiba and JBIC have also signed a strategic relationship agreement (SRA) with U1, and a Uranium Offtake Agreement".[67]

In late 2010, the Japanese partners sold their share of Uranium One to a subsidiary of Rosatom, Atomredmetzoloto JSC (ARMZ Uranium Holding Company).[68] A condition of the sale was that

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[64] Tifa Asrianti, "RI Unfazed by Japan Nuclear Crisis", *Jakarta Post*, 15 March 2011 , [retrieved 18 March 2011] <http://www.thejakartapost.com/news/2011/03/15/ri-unfazed-japan-nuclear-crisis.html>

[65] World Nuclear Association, 2 March 2011 [retrieved 17 March 2011] <http://www.world-nuclear.org/info/inf48.html>

[66] "World Nuclear Power Reactors & Uranium Requirements," World Nuclear Association, 2 March 2011 [retrieved 17 March 2011] <http://www.world-nuclear.org/info/reactors.html>

[67] Tokyo Electric Power, "Toshiba and Japan Bank for International Cooperation to Acquire 19.95% Equity Interest in Uranium One of Canada - Establishment of Long Term Strategic Alliance with Strategic Relationship Agreement and Uranium Offtake Agreement," TEPCO Pres Release, February 10, 2009, [retrieved 17 March 2011] <http://www.tepco.co.jp/en/press/corp-com/release/09021001-e.html>

[68] Uranium One Inc. Company Links, WISE, 27 December 2010, [retrieved 17 March 2011]

TEPCO and other Japanese companies, “receive purchase rights for up to 2.5 million pounds of natural uranium (U3O8) a year from 2014 to 2025, against the current right to up to 20 percent of U1's annual attributable production.”[69]

The Australian government made no public statement on uranium exports immediately following the onset of the Fukushima crisis. However, senior industry and political figures on both sides of politics had until that time been strenuously advocating the need for both expanded uranium mining and a reconsideration of the decision to not build nuclear power plants in Australia.[70] Executives in uranium mining companies, including BHP and Rio Tinto, facing huge slumps in share prices put on a brave face, with one saying that, “the Japanese disaster won’t affect major demand centres of China, India and Russia – only decision making in Australia and Germany.”[71]

While one senior Australia scientists called the reaction to the Japanese nuclear situation "hysterical"[72], David Sweeney, a campaigner for the Australian Conservation Foundation, the largest environment organisation in the country, linked Australia directly to the Fukushima crisis, saying, "it's actually possible that it is Australian uranium that has derived the nuclear material that may be leaking and exploding in those reactors in Japan.”[73]

6. Fukushima I Nuclear Generating Station, Site Stabilization and Recovery

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<http://www.wise-uranium.org/ucscr.html>

[69] “TEPCO, Toshiba Corporation and JBIC Redefine Relationship with Uranium One,” *JBIC*, August 9, 2010, [retrieved 17 March 2011] <http://www.jbic.go.jp/en/about/press/2010/0809-01/index.html>

[70]See, for example, “Australia's Ferguson Wants to Expand Uranium Exports, Sell to India,” *Reuters*, 9 March 2011, [retrieved 17 March 2011] <http://www.reuters.com/article/2011/03/09/australia-resources-uranium-idUSL3E7E90W420110309>

[71]Peter Ker, “Reactor Reaction Wipes $1.5bn from Uranium Holdings,” *Sydney Morning Herald*, March 15, 2011, [retrieved 17 March 2011] <http://www.smh.com.au/business/reactor-reaction-wipes-15bn-from-uranium-holdings-20110314-1buh0.html>

[72]Australian Scientist Downplays Fukushima Threat” AM, *ABC Radio* March 16, 2011, [retrieved 17 March 2011] <http://www.abc.net.au/am/content/2011/s3165067.htm>

[73] Jeannette McMahon, “Japan's Nuclear Crisis Causes Reaction in Australia,” ABC Radio Newcastle, 16 March 2011 [retrieved 17 March 2011] <http://www.abc.net.au/local/audio/2011/03/16/3165513.htm?site=newcastle>

This site has six operational reactors (Units 1-6) and two under construction (units 7-8). Units 1-3 were in operation when the earthquake and tsunami struck, while units 4-6 were shut down for maintenance. Each of the six operational reactors has a spent-fuel pool high up in the reactor building, immediately adjacent to the containment vessel. In addition, an independent spent-fuel pool and an independent facility for dry-cask storage of spent fuel are located on the site.

Thus, reactor fuel that was active prior to the earthquake or was previously discharged from a reactor is now present at the site in up to fourteen locations – six reactor cores, seven spent-fuel pools, and one dry-cask storage facility. However, reports indicate that the reactor core of unit 4 had been entirely transferred to the adjacent spent-fuel pool prior to the earthquake, which reduces the number of locations to thirteen.

At the time of writing, reports indicate that the site is in "station blackout", a situation in which no AC power is available. Fuel in the cores of units 1-3 and, apparently, fuel in the unit 4 spent-fuel pool has suffered damage, the status of the fuel in the spent-fuel pools at units 1-3 is unclear, and other fuel is said to be undamaged at present. The reactor buildings of units 1-4 are damaged, and the containment vessels of units 2-3 are presumed to be damaged. The fuel that is damaged has undergone an exothermic reaction with steam, yielding hydrogen that has exploded at various locations in units 1-3 and, apparently, in unit 4. The nature and extent of the fuel damage is unclear, but could include rupture, oxidation, and melting of zircaloy cladding, together with melting of fuel pellets and slumping of fuel structure. A small fraction of the radioactive material in the affected fuel has been released to atmosphere, and an additional fraction has been deposited along the release pathway.

Cooling of reactor cores and spent-fuel pools is currently being provided by addition of seawater. The seawater is evidently being provided via ad hoc piping arrangements that presumably include engine-driven pumps and flexible hoses. In addition, helicopters are dumping seawater on reactor buildings, and trucks equipped with water cannons are spraying seawater on these buildings. The effectiveness of these measures is questionable. Operation of the site is being done by a skeleton crew functioning in a radioactively-contaminated environment, and the site has experienced a sequence of explosions and fires. This situation poses a number of risks. For example, operator errors are likely, and seawater cooling in a hot environment could lead to corrosion or crystallization that disables instruments, valves, etc.

A range of possible outcomes could occur over the coming days and weeks. At the high end of the range of severity of outcomes, there could be substantial releases to the atmosphere from up to five reactor cores and seven spent-fuel pools. A release from the dry-cask storage facility is unlikely. One favorable factor at this site is that the reactor-adjacent spent-fuel pools are not packed as tightly as in current US practice. Thus, the fuel in these pools may be less prone to spontaneous ignition if water is lost from the pools.

There is clearly an urgent need for implementation of a systematic plan to stabilize the reactor cores and spent-fuel pools at this site. That plan would involve the provision of a copious, reliable supply of fresh water at each of these locations. The plan could also encompass restoration of AC power, construction of radiation shields, redirection or capture of contaminated effluents, clearing of debris, measures to compensate for damaged containment vessels, improved fire protection, etc.

Implementing this plan would involve bringing to the site a variety of materials (e.g., fresh water) and equipment (e.g., truck-mounted cranes), together with skilled personnel and facilities to support them. In view of the scale of damage to regional infrastructure, and the degraded condition of site facilities, it seems likely that the needed assets would best be brought to the site on barges or roll-on/roll-off ships. It could be appropriate to dock some vessels at the site for an extended period, so that they provide an independent base for stabilization operations.

Whatever plan is adopted for immediate stabilization, it should be designed to transition over a period of months to a site-recovery plan. That plan would be implemented over a period of years. It would involve the packaging and removal from the site of degraded fuel and contaminated equipment, decommissioning of facilities that can no longer function, and decontamination of the site to pre-earthquake levels.

Japan has the technical and human capabilities to independently implement a site-stabilization plan followed by a site-recovery plan. However, in view of the many burdens placed upon Japan by the earthquake and the tsunami, assistance from other countries could be very helpful. The United States, Russia, Europe, China, South Korea, and other powers have relevant capabilities. An immediate joint initiative by such powers to help Japan with the stabilization and recovery of this site could have great practical value and could create lasting goodwill among the participating nations.

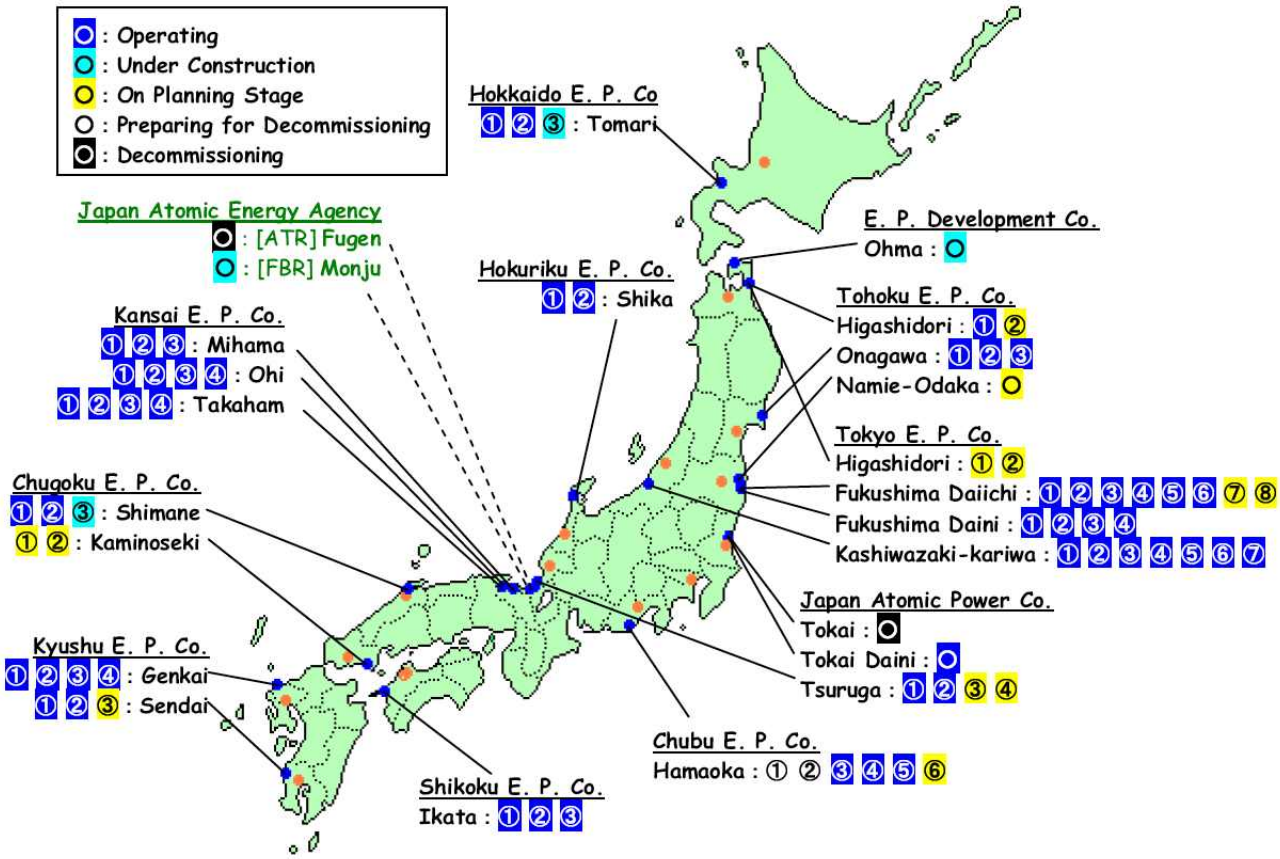
The overall effort would need strong leadership and effective coordination, which likely exceeds the authority of the IAEA. In Europe, the Chernobyl recovery operation required a regional effort, and was led by the Chernobyl Shelter Fund, managed by the European Bank for Reconstruction and Development (EBRD). East Asia currently lacks an equivalent organization.

After the Deluge Short and Medium-term Impacts of the Reactor Damage Caused by the Japan Earthquake and Tsunami
Nautilus Institute for Security and Sustainability
March 17, 2011

Given the importance of prompt and efficient action, it might be appropriate for the UN Security Council to establish an ad hoc coordination mechanism under its auspices, with leadership delegated to one of the great powers.

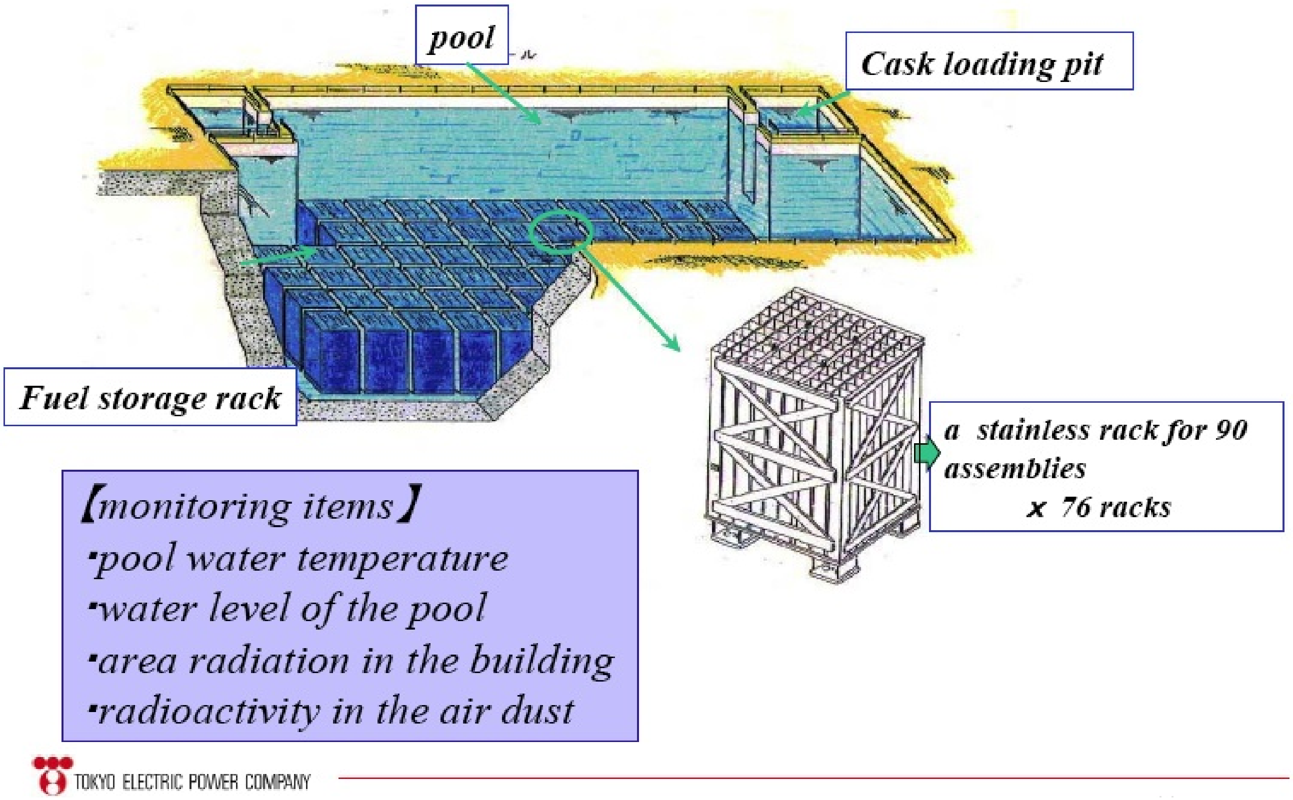
Attachments

Attachment 1. Nuclear power stations in Japan (as of 2008) - map[74]

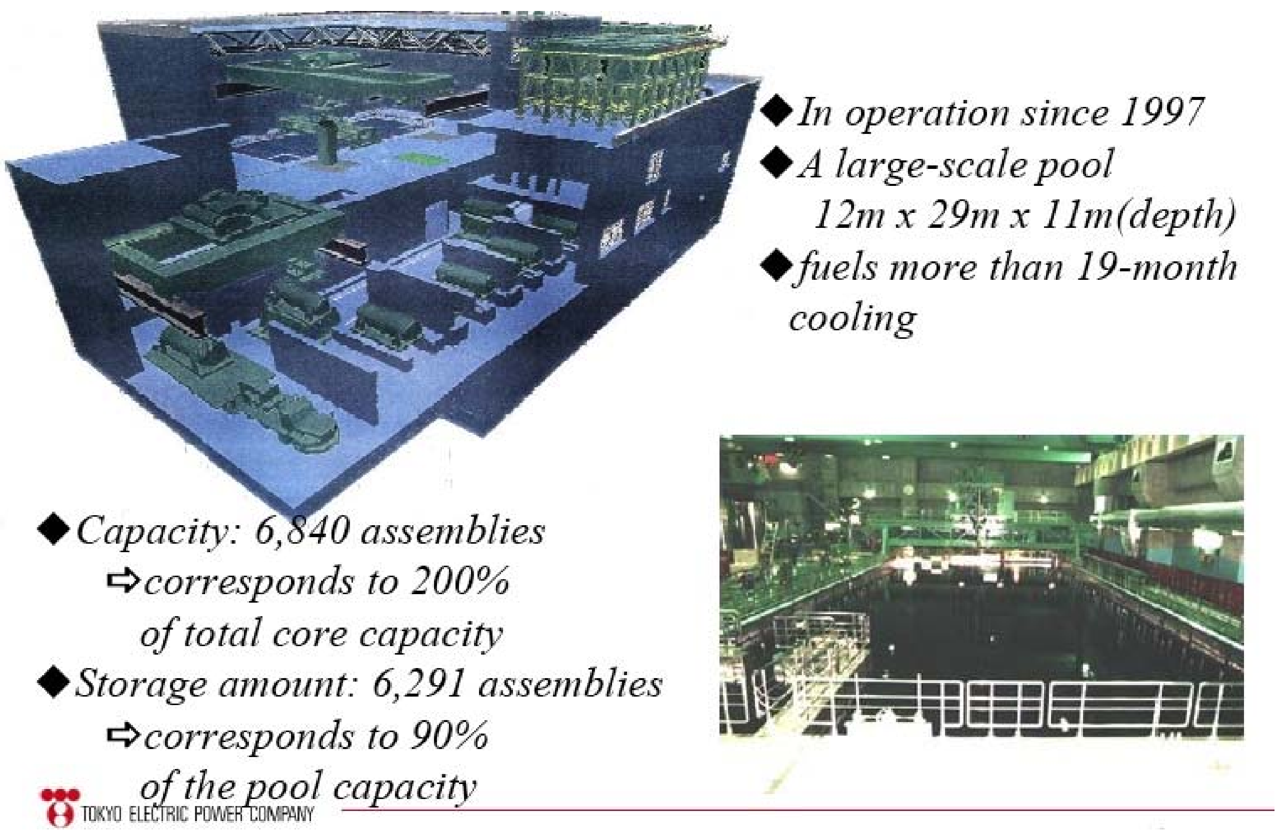


[74] "Current Status of Nuclear Facilities in Japan," Japan Nuclear Energy Safety Agency, 2009, [retrieved 16 March 2011] <http://www.jnes.go.jp/english/activity/unkan/e-unkanhp1/e-unkanhp1-2009/book1/>

Attachment 2: Outline of common spent fuel storage facility at Fukushima NPP I



Attachment 3: Outline of common spent fuel storage facility at Fukushima NPP I



Attachment 4: Reactor processes at Fukushima NPP I

When the earthquake hit on March 11, 2011 at 2:46 pm JST, units 1, 2 and 3 of the Fukushima I nuclear power plant site were shutdown automatically, while units 4, 5 and 6 were not in operation because of periodic inspection. Due to the tsunami that flooded into the area about a half hour after the earthquake, there was a loss of offsite AC mains power, and subsequently a breakdown of several emergency diesel generators at the site. Following this breakdown of the diesel generators, onsite batteries with a relatively short life took over supply of power to water pumps. After the reactors shut down, over the four days following March 12, pumps to units 1, 2, and 3 failed to maintain an adequate supply of coolant, resulting in hydrogen explosions at the containment buildings of each of the three reactors.

The reactors at Fukushima I nuclear power plant site are all Boiling Water Reactors (BWR). Since there was no power available for the reactors after the tsunami flooding, the pumps that circulate cooling water was not working, so that the emergency core cooling system (ECCS) does not work. This leads to a loss of coolant accident in the reactors. After the shutdown of a reactor, the fission reaction of fissile materials in nuclear fuel ceases. However, the fuel still releases heat due to decay of radioactive materials that have been produced during fission of fissile materials in the fuel. The residual heat from the fuel drops sharply after shutdown, and then drops slowly with time, e.g. about 1% of the thermal power of the reactor in one day after shutdown, while about 0.2% of that in a year. The residual heat boils water contained in the core. When the cooling systems are not working, the typical rate of water boiling away from the reactor is about 90 gallons per minute in a day after shutdown.[75] It means that more than about 500 tons of water boils away from the core for a day after shutdown.

As the water level drops, the fuel in the core is partially uncovered. In the absence of cooling, the uncovered part of the fuel is overheated to about 900 ºC, where the zircaloy cladding would begin to burn in the air.[76] When heated further to above 1100 ºC, the zircaloy cladding would rapidly react with the steam to oxidize the zirconium and release hydrogen.[77] At about 1850 ºC the zircaloy cladding would melt. The released hydrogen leaks from the reactor vessel into the containment that is kept inert with nitrogen gas to prevent hydrogen gas combustion. When the

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[75] D. Lochbaum, "Reactor Core Cooling", *All Things Nuclear*, March 14, 2011. , <http://allthingsnuclear.org/post/3859682324/reactor-core-cooling>

[76] R. Alvarez et al, "Reducing the Hazards from Stored Spent Power-Reactor Fuel In the United States", *Science & Global Security*, 11 (1), 2003.

[77] Jan Beyea and Frank von Hippel, "Containment of a Reactor Meltdown", *Bulletin of the Atomic Scientists*, August/September 1982

hydrogen is vented into the outer containment in the reactor building, it builds up, mixes with air, resulting in an explosion, as occurred in the units 1, 2 and 3 reactors.

The partly melted spent fuel also releases cesium-137 and iodine-131 that are volatile radioactive isotopes which build up in the fuel as a result of fission of fissile materials in the fuel. Due to destruction of the reactor buildings of the units 1, 2 and 3, the leaked cesium-137 and iodine-131 from the reactors were detected outside the site.

Attachment 5. Partial list of damaged industrial facilities

(as of 1 pm, 14 March 2011)[78]

Nippon Steel Corporation:

- Kamaishi factory (Iwate prefecture): A part of the steel plant is flooded, and the production is stopped. Harbor facility is damaged, and is not anticipated to recover.
- Kimizu factory (South Chiba): Three blast furnaces stopped after an aftershock on the afternoon of 13th. Rolling process and following process are recovering gradually.
- Tokyo factory: Stopped by the planned power outrage.

JFE Steel:

- East Japan factory: Furnaces in Keihin (in between Yokohama and Tokyo) area restarted on the 13th. Furnaces in Chiba restarted on the 14th. In order to support efforts to save electricity demand, furnaces are under safety mode, and other lines are basically stopped.

Sumitomo Metal Industries:

- Kashima factory (Ibaraki): All lines are stopped. Fire on gas container was extinguished. Damage on gas container, cokes furnaces, blast furnaces, dock crane resulted from the earthquake. No damage from the flood was observed. It is expected that all facilities can recover in a short while.

Nisshin Steel:

- Ichikawa factory (Chiba): No damage

Chuo Denko

- Kashima factory: All production is stopped. Damage level is being investigated.

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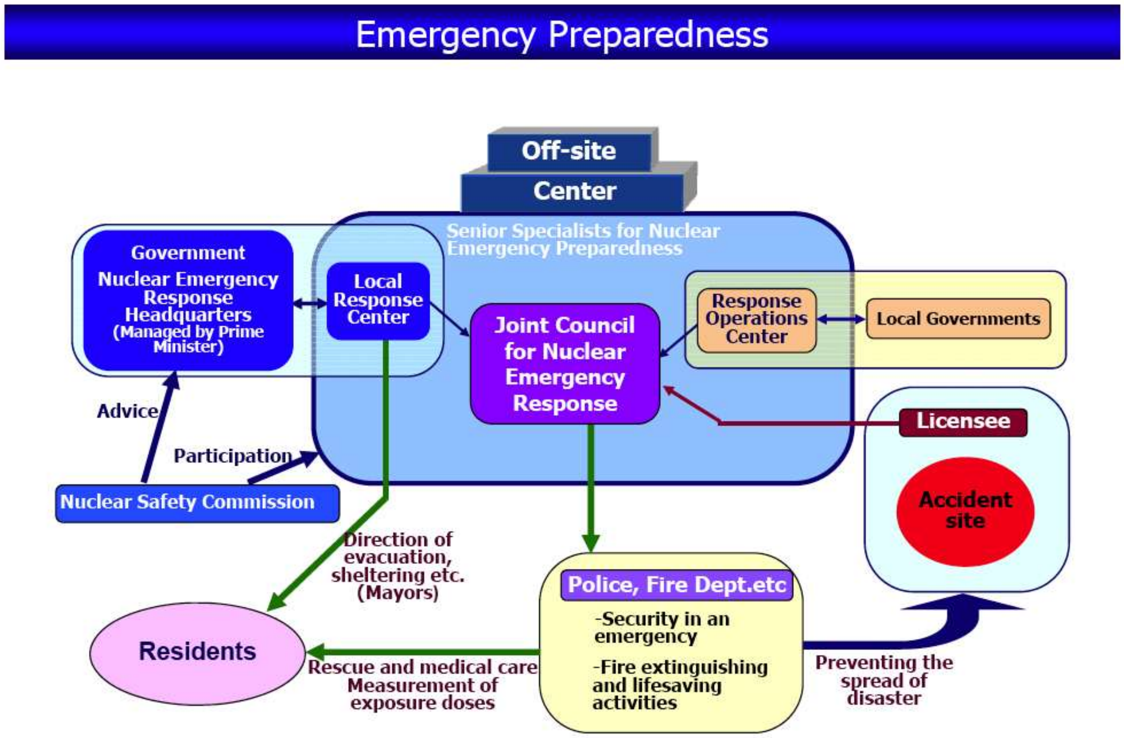
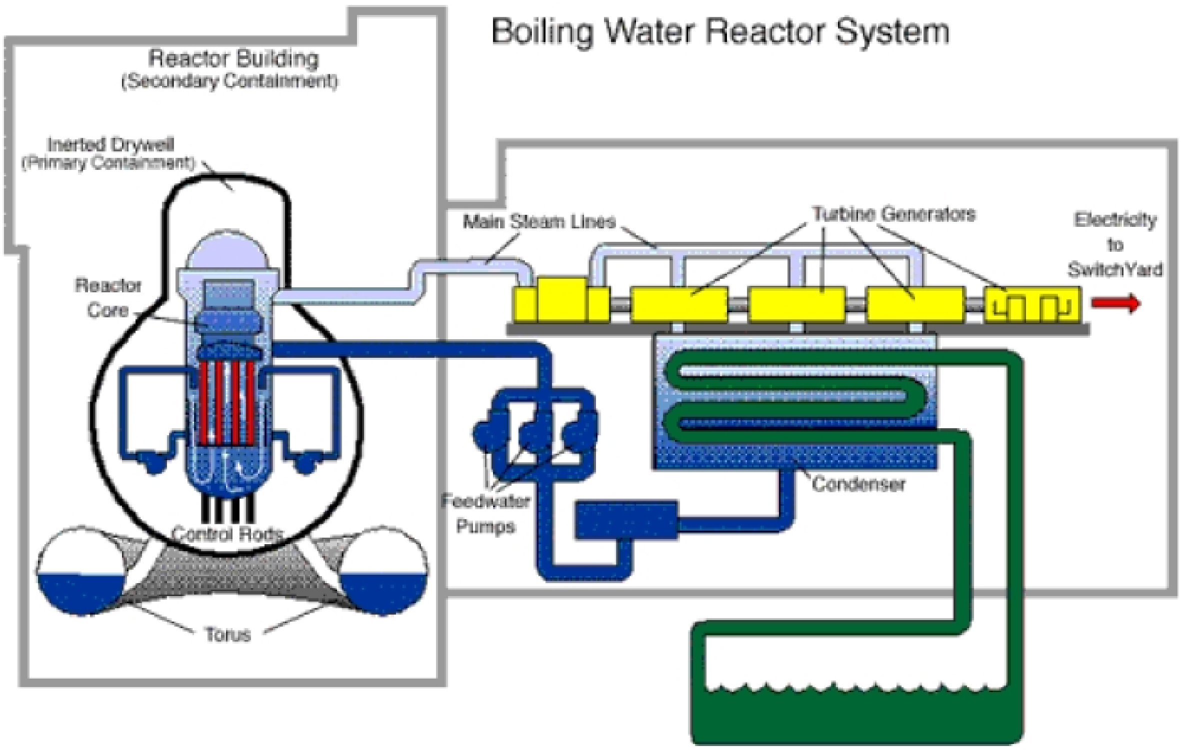
[78] 地震被害、復旧めど立たず　グループ総力で対応, Japan Metal News/日刊産業新聞, 15 March 2011, [retrieved 16 March 2011] <http://www.japanmetal.com/back_number/news/newsidt2011031501.html>

Attachment 6: Emergency preparedness, Japan Nuclear Energy Safety Organization [79]



[79] "Overview of Nuclear Safety Regulation in Japan," Japan Nuclear Energy Safety Organization, December 2010, [retrieved 16 March 2011] <http://www.ansn-jp.org/jneslibrary/fa006r11.pdf>

Attachment 7: Boiling Water Reactor System[80]



[80]Hideki Takano, "Introductory Nuclear Design," Institute of Applied Beam Science, Ibaraki University, *Asian Nuclear Safety Network*, SA-L-5, p.2 [retrieved 16 March 2011] <http://www.ansn-jp.org/item_file/2004-SA-L-05.pdf#search=%27boiling%20water%20reactor%27>

Attachment 8: BWR Nuclear Fuel Structure[81]

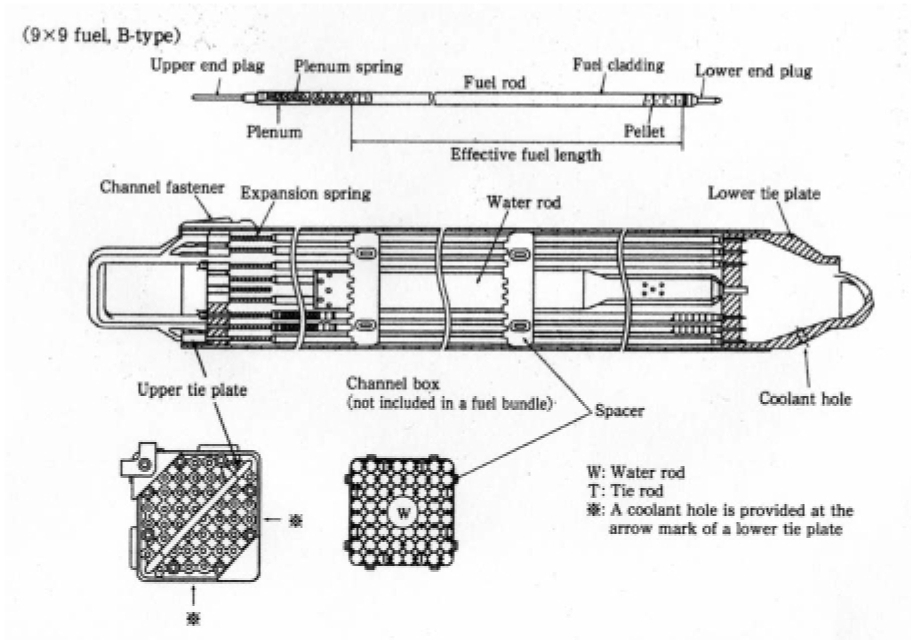


Figure 4. **BWR Nuclear Fuel Structure**

[81] "Boiling Water Reactor Power Plant," *Asian Nuclear Safety Network,* September 2007, p. 7.

Attachment 9 : Shielding types for BWR

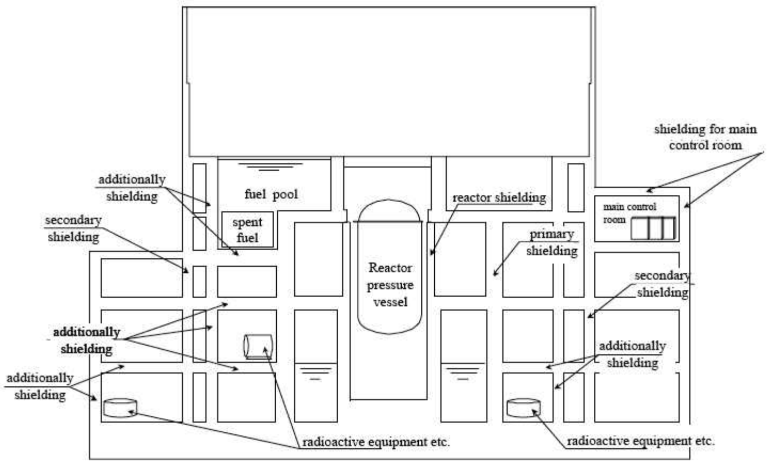


Fig. 4-1 Explanation drawing for summary of shielding type (BWR)

by JEAG4615-2003

(1) Shielding of nuclear reactor
It attenuates the radiation from nuclear reactor in operating time.

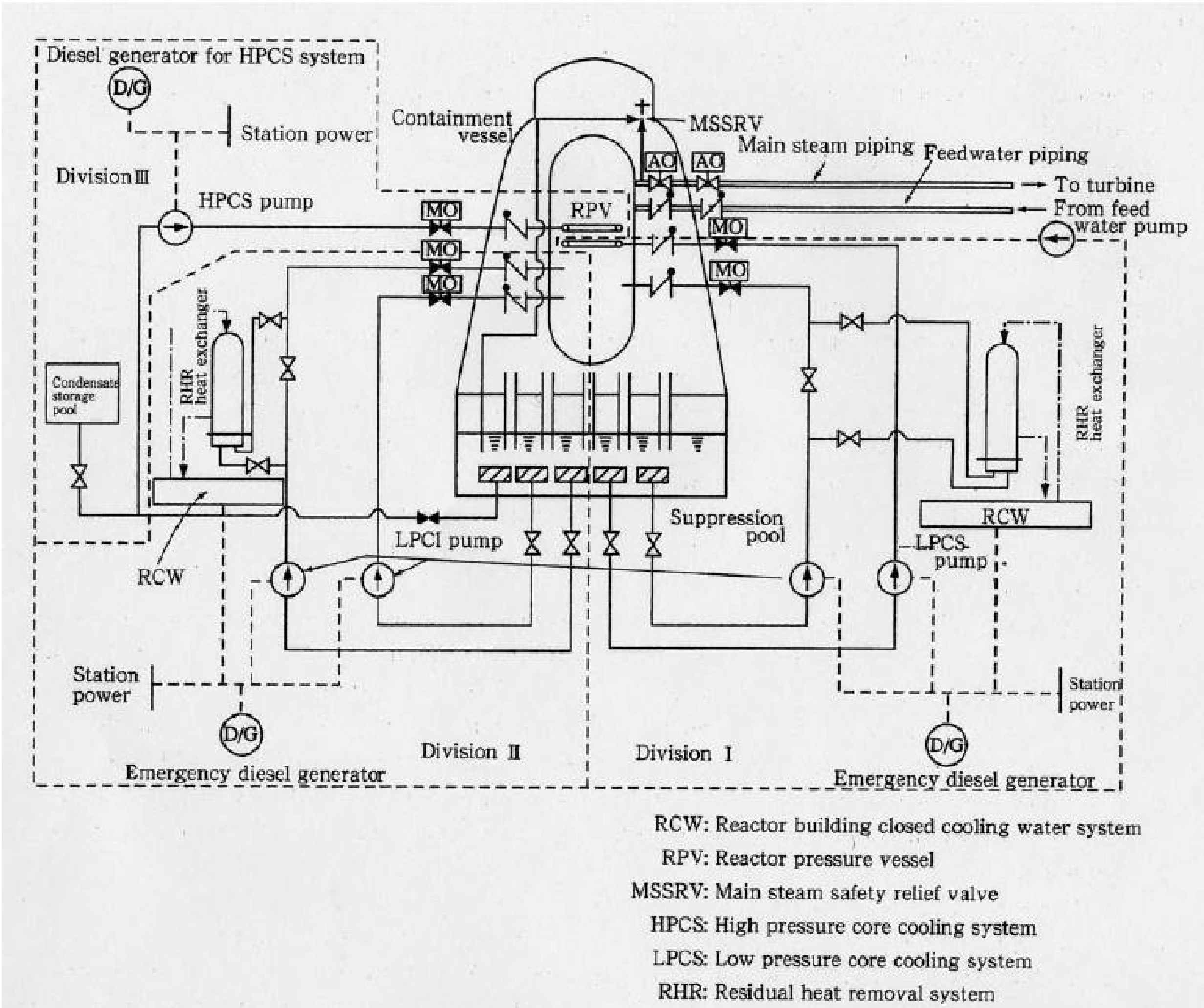
(2) Primary shielding
It is a structure which surrounds a reactor container. It fulfill the dose rate to be under the designing reference dose rate outside shielding.

(3) Secondary shielding
It attenuates the dose rate under the reference value for outside controlled area. Additionally, it reduces the dose for public in accident.

(4) Additional shielding
It is a structure which surrounds equipments, for example, devices include radioactive materials, pipes, and so on. Additionally, it makes the dose rate for outside area under the designing reference dose rate.

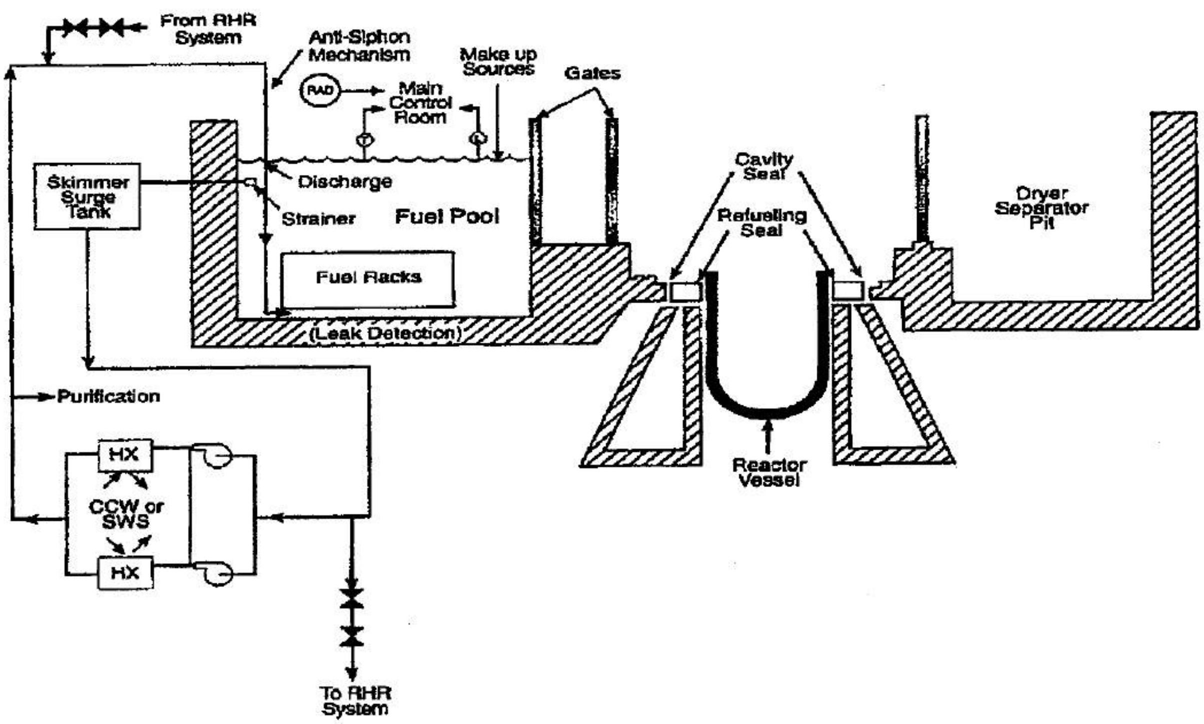
(5) Shielding for main control room
In normal operation, it makes dose rate under the designing reference dose rate for non-controlled area. While it designed to keep operators out of excessive exposure in accident.

Attachment 10: ECCS Network for BWR-5, 1100MWe[82]



[82] "Boiling Water Reactor Power Plant," *Asian Nuclear Safety Network,* September 2007, p. 9.

Attachment 11: Layout of spent fuel pool and transfer system for boiling water reactors [83]



[83] Robert Alvarez, Jan Beyea, Klaus Janberg, Jungmin Kang, Ed Lyman, Allison Macfarlane, Gordon Thompson, Frank N. von Hippel, "Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States," *Science and Global Security,* 11:1–51, 2003, p. 6; citing J. G. Ibarra, W. R. Jones, G. F. Lanik, H. L. Ornstein and S. V. Pullani, "Operating Experience Feedback Report: Assessment of Spent Fuel Cooling" (NRC, NUREG-1275, 1997), Vol. 12. [retrieved 17 March 2011] <http://www.irss-usa.org/pages/documents/11_1Alvarez.pdf>

Attachment 12: Safety design of Boiling Water Reactors

Extract from Senji Kato, "Safety Design and Safety Evaluation of BWR," ***Asian Nuclear Safety Network,*** **SA-L-18 pp. 3-5**

Safety design

Maintaining safety of nuclear power stations means to prevent the potential risks of radioactive materials, which are inherent in nuclear power stations, from becoming manifest. The safety design of nuclear power plants comprise the following three-layer safety measures:

1. Prevention of anomaly development (first layer)
2. Prevention of anomaly expansion (second layer)
3. Prevention of the abnormal release of radioactive material (third layer)

This safety design concept is generally called "defense in depth." In the case of an accident, safety measures taken based on this concept perform the following actions:

- Shutting down the reactor
- Cooling the reactor
- Confining radioactive material

Safety measures implemented at each layer are specified below:

(1) Measures to prevent anomaly development

To prevent accidents, it is critical to prevent the anomalies such as component failure/degradation that may cause an accident. In this respect, following features are provided to prevent anomaly development:

(a) Sufficient Margins in Design

Components and systems are designed to withstand their operating conditions such as pressure and temperature with sufficient margins.

(b) Design features to prevent an operator error/inadequate actuation

This is accomplished by adopting systems like inter-locking system and fail-safe system. The inter-locking system defines specific conditions to actuate systems and prevents an operator error by prohibiting an actuation in inappropriate conditions. The fail-safe system is a system which forces to remain in a safe status in case of a failure in a subsystem. For example, scram would be initiated in case of loss of electric power.

(c) Surveillance/inspections of components

Component surveillance test are scheduled during normal operation, and detailed inspections are done during planned outage in every year.

(2) Measures to prevent anomaly expansion

In case an anomaly occurs despite these development prevention measures, a different set of measures is required to prevent any anomaly from expanding into an accident. Nuclear power stations are designed so that anomalies can be found at the early stage and the reactor can be put into a scram ("shut down").

To enable early discovery of anomalies, many sensors are provided in independent, multiple, and diverse way.

To shut down the reactor in an emergency, a scram system is provided. When a plant anomaly signal is detected by the reactor protection system, all control rods are promptly and entirely inserted by water pressure. The control rods are designed to have enough control capability, providing a sufficient shutdown margin when the core is in a cold-shutdown status. In addition, to maintain the reactor subcritical as the nuclear system cools, the standby liquid control system to pump a boron neutron absorber solution into the reactor is provided.

(3) Measures to prevent the abnormal release of radioactive material

In case an anomaly expands further in spite of the above prevention measures, another set of measures is required to suppress the possible impact of radioactive release on the neighboring environment, namely, measures to "cool" the reactor and "confine" the radioactive material. For this purpose, engineered safety features such as the emergency core cooling system (ECCS) and reactor containment facilities are provided.

(a) ECCS

The ECCS is a set of safety systems that inject cooling water to the core when a reactor accident such as a loss of coolant occurs, preventing fuel cladding damage. The ECCS comprises the low pressure coolant injection function of the residual heat removal systems, high and low pressure core spray systems, and automatic depressurization of the primary system. These systems are automatically activated in the case of a reactor accident, injecting water to the reactor from the condensate storage tank or from the containment suppression pool.

(b) Reactor containment facilities

Reactor containment facilities consist of the PCV (the primary containment facility) and the reactor building (the secondary containment facility).

1. PCV

The BWR PCV has a suppression pool (chamber) inside. This vessel has a pressure suppression function, which, by means of the suppression pool, cools and condenses the steam emitted when the safety relief valve is activated or when the loss-of-coolant accident (LOCA) occurs. Thus the PCV is constructed to withstand such pressure as well as temperature and hydrothermal loads.

In addition, to cool atmosphere in the PCV and to remove radioactive iodine floating in atmosphere, the PCV spray system is provided.

2. Reactor building

The reactor building houses reactor components including the PCV itself. At the same time, it functions as part of the reactor containment facilities in cooperation with the PCV; hence it is called the secondary containment facility. The building is a sealed structure and is designed to shield radiation.

To prevent radioactive material from escaping the building in the case of an accident, air in the building is maintained at a negative pressure relative to atmospheric pressure. When the LOCA occurs, the stand-by gas treatment system (SGTS) is activated to remove fission products (FPs) which leak from the PCV to the reactor building.

Attachment X: Types of Shielding in Boiling Water Reactor[84]

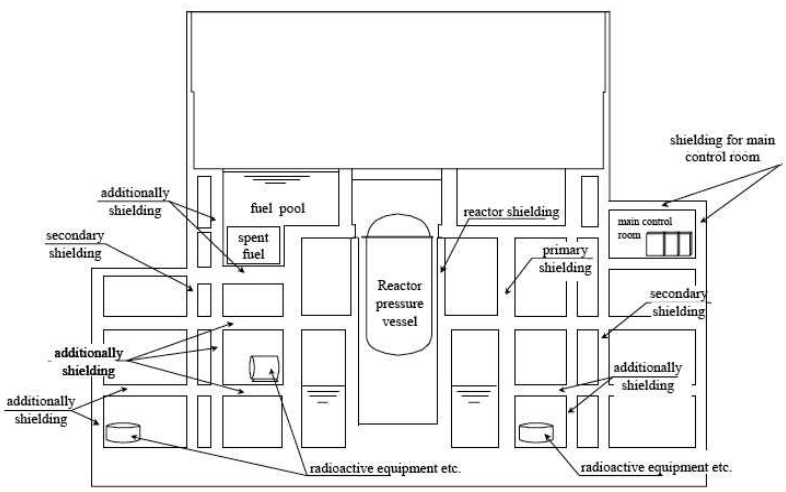


Fig. 4-1 Explanation drawing for summary of shielding type (BWR)

by JEAG4615-2003

(1) Shielding of nuclear reactor
It attenuates the radiation from nuclear reactor in operating time.

(2) Primary shielding
It is a structure which surrounds a reactor container. It fulfill the dose rate to be under the designing reference dose rate outside shielding.

(3) Secondary shielding
It attenuates the dose rate under the reference value for outside controlled area. Additionally, it reduces the dose for public in accident.

(4) Additional shielding
It is a structure which surrounds equipments, for example, devices include radioactive materials, pipes, and so on. Additionally, it makes the dose rate for outside area under the designing reference dose rate.

(5) Shielding for main control room
In normal operation, it makes dose rate under the designing reference dose rate for non-controlled area. While it designed to keep operators out of excessive exposure in accident.

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[84] Hiroshi Nakashima, "Introductory on Shielding Design for Nuclear Facilities," Quantum Beam Science Directorate, Japan Atomic Energy Agency, *Asian Nuclear Safety Network*, SA-L-9, [retrieved 16 March 2011] <http://www.ansn-jp.org/item_file/2005-SA-L-9.pdf#search=%27boiling%20water%20reactor%27>