

## BRC MEMORANDUM

**Date:** May 10, 2011  
**Memorandum for:** Commissioners  
**From:** BRC Staff  
**Subject:** Overview of the Accident at the Fukushima-Daiichi Nuclear Complex

The first two presentations at the May 13<sup>th</sup> Commission meeting will cover reviews being conducted by the federal government in response to the natural disaster and resulting nuclear accident at the Fukushima Daiichi plant in Japan. The purpose of those presentations is to hear from the U.S. Nuclear Regulatory Commission and the U.S. Department of Energy about what steps are being taken to review the safety of domestic nuclear reactor and spent fuel storage facilities in light of the events in Japan. This memorandum provides an overview of the accident and the announced plans for recovery and remediation.

### Overview

On March 11, 2011, a massive earthquake occurred, with an epicenter approximately 45 miles off the coast of the Tōhoku region of Japan. The earthquake's magnitude has been estimated at 9.0 on the Richter scale. The epicenter was approximately 109 miles from the Fukushima Daiichi reactor site.<sup>1</sup> The earthquake was the fourth-largest recorded in the world since 1900, and the largest in modern Japanese history. The earthquake (which has been officially named the Eastern Japan Great Earthquake Disaster) triggered an immense tsunami that devastated large areas of the eastern Japanese coast. Over twenty thousand people are known dead, and thousands more are missing. Damage estimates are unknown at this time but could amount to several hundred billion dollars.

According to Japan's Nuclear and Industrial Safety Agency (NISA), the earthquake and subsequent tsunami affected fourteen nuclear reactors at four sites along the eastern coast – the Fukushima Daiichi site (six reactors), Fukushima Daini site (four reactors), the Ongawa site (three reactors) and the Tokai site (one reactor).<sup>2</sup> The most serious damage occurred at the Fukushima Daiichi Nuclear Power Station. When the earthquake struck, the three reactors at the site that were operating at the time—Units 1, 2 and 3—automatically shut down. Unit 4 had been shut down about three months before the event and its core unloaded into its spent fuel pool, and Units 5 and 6 had also been shut down well before the event.

Offsite power was lost at Fukushima Daiichi because of the earthquake, and operators switched to emergency backup diesel generators to run the plant's cooling systems. Approximately one hour later, at 3:41pm on March 11, a tsunami estimated at up to 14 meters struck the plant,

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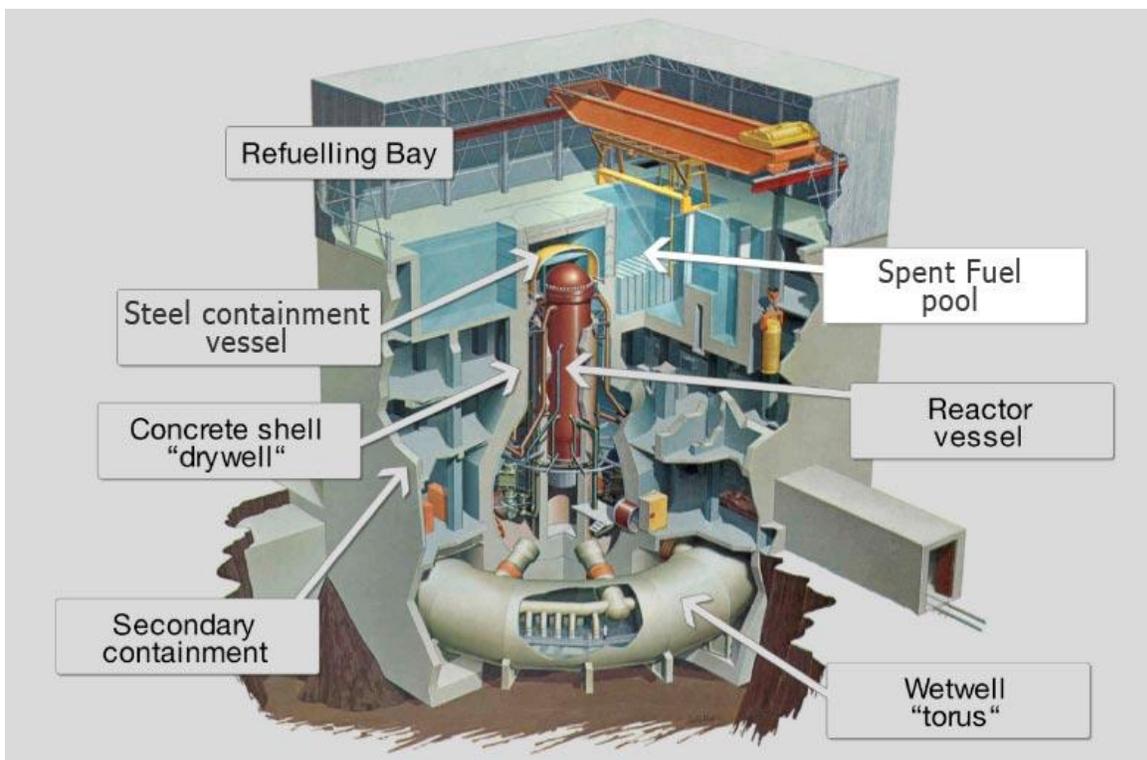
<sup>1</sup> NRC ACRS Briefing, p. 120.

<sup>2</sup> Nuclear Regulatory Commission, presentation to the Advisory Committee on Reactor Safeguards, April 7, 2011 (hereinafter referred to as "NRC ACRS Briefing;" transcript available at <http://pbadupws.nrc.gov/docs/ML1110/ML11102A041.pdf>)

flooding the backup generators, their fuel supply, and electrical switchgear and causing an extended blackout at the entire station (a similarly-sized tsunami wave also struck the Fukushima Daini plant, but the backup power systems survived and plant cooling was fully restored within a week). The flooding of the switchgear and many electrical motors with salt water made this equipment unusable, and the requirement to replace this equipment contributed to greatly slowing efforts to reenergize electrical systems. The Fukushima Daiichi's plant design basis included an estimated maximum credible earthquake and tsunami. Although the ground acceleration from the earthquake was close to or beyond the reactors' design bases and the physical structures appear to have survived the quake, the tsunami greatly exceeded the design basis tsunami and knocked out both offsite power supplies and the on-site backup diesel generators.

Even when a reactor shuts down, as Units 1, 2 and 3 did after the earthquake, the fuel in the reactor core still emits a great deal of radiation and heat – about six percent of full-power levels – due to the decay of radioactive fission products in the fuel. With offsite power and the diesel generators unavailable, the reactor core isolation cooling (RCIC) systems in Units 2 and 3, and the isolation condenser system in Unit 1, relied on battery power for several hours after the tsunami struck to keep the fuel in the reactors cool. The Unit 1 isolation condenser boiled dry at 4:36 pm on March 11, leading to the loss of ability to cool the reactor. Subsequently the Unit 3 RCIC failed at 5:10a on March 13, and the Unit 2 RCIC at 1:25p on March 14.

With the loss of the backup cooling systems, the water in the reactors heated up and ultimately boiled off in amounts sufficient to uncover at least part of the fuel in the reactor cores in Units



**Schematic of a Boiling Water Reactor (Source: IAEA)**

1, 2 and 3. This caused the pressure inside the reactor's steel primary containment vessel to build up from the generation of steam and hydrogen gas. To control the pressure in the primary containments, operators were required to vent some gases. For an unknown reason, flammable gases from the venting, which should have been directed out through the plant stacks, instead accumulated in reactor buildings and subsequently exploded, damaging the reactor buildings at Units 1 and 3. Unit 2 also suffered a hydrogen explosion ("deflagration") in its primary containment building, but the extent of the damage to its secondary containment was much less than at the other three units.<sup>3</sup>

Unit 4, which was shutdown and defueled at the time of the tsunami, also suffered an explosion that severely damages its reactor building. The flammable gas that exploded in Unit 4 came from an unknown source. It may have been generated by fuel in the storage pool which might have become uncovered, but this has not been confirmed.

Ultimately, the damage to fuel in the Unit 1, 2 and 3 reactors was stopped by actions to connect portable pumps (fire trucks) to inject seawater into the reactor vessels to provide cooling. The action to initiate seawater injection took 27 hours to complete after Unit 1 lost backup cooling, and approximately 7 hours after Unit 2 and Unit 3 lost cooling. There is still considerable uncertainty regarding the precise cause and progress of events leading to explosions and radionuclide releases, in part because instrumentation was not available to measure key plant safety parameters such as water inventories in spent fuel pools and reactor and turbine building sumps.

As of late April 2011, the status of the reactors at the Fukushima Daiichi station is believed to be the following:<sup>4</sup>

- The reactor cores in Units 1, 2, and 3 have been severely damaged. Tokyo Electric Power Company (TEPCO) estimates that the cores have sustained damage (i.e., melting of the fuel elements) ranging from 55 percent (Unit 1) to 35 and 30 percent for Units 2 and 3. For purposes of comparison, the reactor meltdown at Three Mile Island was between 50 and 75 percent.
- The cores also have extensive buildup of salt as the result of emergency injection of seawater into them in an effort to cool the reactors. Fresh water is now being used to cool the reactors, so no new salt is being added. Nitrogen is also being injected to reduce the potential for additional explosions. The initial addition of salt water is expected to accelerate corrosion processes, and will be one factor complicating long-term management of the accident.
- High radiation levels have been detected in the containment buildings and around the reactor site. It is believed one or more of the building explosions ejected radioactive material around the site. Radiation readings in the buildings and around the site have

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<sup>3</sup> NRC ACRS Briefing, p. 14.

<sup>4</sup> NRC ACRS Briefing, p. 19.

been trending downward but are still hampering efforts to stabilize the site and begin mitigation efforts.

- At Unit 4, as noted earlier, the reactor core had been unloaded about three months before the earthquake and tsunami occurred. The cooling system of the spent fuel pool at Unit 4 ceased to function, and makeup water needed to be added to the pool using a truck normally used for pumping concrete. Water continues to be added periodically to all the units' spent fuel pools, most extensively at the Unit 4 pool.<sup>5</sup> Recent video taken inside the Unit 4 pool shows that the fuel is in intact and largely or completely undamaged condition (Figure 1).
- Units 5 and 6 at Fukushima Daiichi were shut down at the time and spent fuel pool cooling is functional at both units. These units are believed to be relatively undamaged.
- There is separate central shared spent fuel pool at the plant site that contains 6,375 spent fuel assemblies, some 60 percent of the spent fuel on-site. That facility appears to have suffered little if any significant damage.<sup>6</sup>
- The plant also has nine dry storage casks containing 408 older spent fuel assemblies; initial reports indicate no significant damage has occurred to these casks.<sup>7</sup> The building housing the casks was flooded during the tsunami.<sup>8</sup>

A great deal of attention has been paid to the spent fuel stored at the Fukushima Daiichi plant and the current state of that fuel. The following table shows the location, types (new or spent), and numbers of fuel assemblies, in the Fukushima Daiichi reactors, spent fuel pools, shared pool, and dry storage facility.<sup>9</sup> Please note that we have seen discrepancies in reports of the plant's actual fuel storage inventories and capacities, so the numbers provided below must be considered preliminary at this time.

Location and Numbers of Fuel Assemblies at Fukushima Daiichi								
Location	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Total all reactors	Shared Pool
Reactor core	400	548	548	0	548	764	2808	0
Spent fuel in pool	292	587	514	1,331	946	876	4546	6,375
Latest addition of spent fuel to pool	Mar-10	Sep-10	Jun-10	Nov-10	Jan-11	Aug-10		
New Fuel in pool	100	28	52	204	48	64	496	0
<b>Total in pool</b>	<b>392</b>	<b>615</b>	<b>566</b>	<b>1,535</b>	<b>994</b>	<b>940</b>	<b>5,042</b>	<b>6,375</b>

<sup>5</sup> Update to Information Sheet Regarding the Tohoku Earthquake, Federation of Electric Power Companies of Japan (FEPC) Washington DC Office, April 26, 2011.

<sup>6</sup> World Nuclear News, Spraying Continues at Fukushima Daiichi, March 18, 2011 (available at [http://www.world-nuclear-news.org/RS\\_Spraying\\_continues\\_at\\_Fukushima\\_Daiichi\\_1803111.html](http://www.world-nuclear-news.org/RS_Spraying_continues_at_Fukushima_Daiichi_1803111.html)).

<sup>7</sup> NRC ACRS Briefing at p. 96.

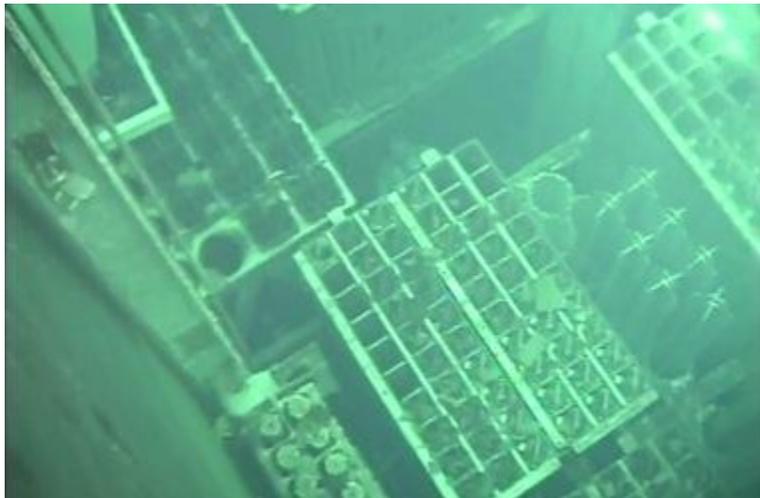
<sup>8</sup> Statement of Lake Barrett at the Nuclear Energy Institute's Used Fuel Management Conference, Baltimore, MD, May 2, 2011.

<sup>9</sup> JAIF Status Report (see Note 10).

<b>Total pool capacity</b>	900	1,240	1,220	1,590	1,590	1,770	8,310	6,840
<b>Remaining pool capacity</b>	508	625	654	55	596	830	3,268	465
<b>Total in dry storage</b>	--	--	--	--	--	--	408	--

The reactor spent fuel pools have high density racking are relatively full, with 5,042 assemblies out of a total capacity of 8,310 assemblies.<sup>10</sup> The freshly offloaded fuel in the Unit 4 pool was apparently closely packed, rather than being distributed in a “checkerboard” pattern

intermingled with older fuel as is required in the United States. The central storage facility at the site, which seems to have escaped serious damage, is nearly full—it only has additional space for some 465 assemblies, only a fraction of the assemblies in the reactor pools that will need to be removed. 408 assemblies are stored in dry casks.<sup>11</sup> The entire core of Unit 4—548 assemblies—had been unloaded into its spent fuel pool for reactor maintenance about three months before March 11<sup>th</sup>. There is no mixed oxide (MOX) fuel in any pools,<sup>12</sup> although some had been loaded in the Unit 3 core. The pools’ inventory may have been relatively high in part because TEPCO had planned to ship SNF from this and other reactor sites to the Recyclable Fuel Storage Center in Mutsu beginning in 2012.<sup>13</sup>



**Video image of spent fuel in the Unit 4 pool, taken March 11, 2011 (source: World Nuclear News)**

### Radiation releases

The accident at Fukushima has already released far more radioactivity than was released at Three Mile Island (and an estimated ten percent of what was released during the Chernobyl accident), but the amounts and effects are still being assessed. Not surprisingly, workers at the site received the greatest radiation exposures, and will continue to be exposed as cleanup efforts continue. 22 workers have received doses over 100 milliseiverts (10 rem or 10,000 millirem), but to date none have reportedly reached 250 milliseiverts (25 rem, or 250,000 millirem).

<sup>10</sup> International Atomic Energy Agency (IAEA), Fukushima Nuclear Accident Update Log, March 22, 2011, available at <http://iaea.org/newscenter/news/2011/fukushima220311.html>

<sup>11</sup> World Nuclear Association (see Note 8).

<sup>12</sup> World Nuclear Association (see Note 8).

<sup>13</sup> World Nuclear Association (see Note 8).

millirem), the limit recently set for emergency workers.<sup>14</sup> An acute lethal dose is on the order of 5000 to 10000 miliseiverts. Three workers were killed at the site as a result of the earthquake and tsunami (not by radioactivity).

Following the hydrogen explosions, radioactive cesium and iodine were detected in the vicinity of the plant, a clear indication of fuel damage. These had been released via venting of gases from the reactors, including an apparent rupture of the suppression chamber at Unit 2.

The population within a 20-kilometer (12.4 mile) radius of the plant has been evacuated; this evacuation was made mandatory on April 21<sup>st</sup>. Residents in the 20-30 kilometer 12.4-18.6 mile) radius have been told to prepare to shelter in place or evacuate, depending on developments.<sup>15</sup> Food grown in the region was banned from sale soon after the event, although restrictions on some products have since been lifted following extensive sampling. Rice in the evacuation and evacuation preparation zones will not be cultivated in 2011.<sup>16</sup> France's nuclear safety agency IRSN estimates the maximum external doses to people living around the plant are unlikely to exceed 30 milliseiverts (3 rem, or 3,000 millirem) in the first year. This is based on airborne measurements taken to date, and has not been confirmed by any other agency. Natural background levels between 2-3 milliseiverts (0.2-3 rem, or 200-300 millirem) would normally be expected in the region.<sup>17</sup>

Gamma radiation measurements onsite close to the reactors decreased greatly when the Unit 3 fuel pool was replenished with water on March 19<sup>th</sup>. Some buildings continue to have very high radiation readings inside, which have been measured remotely using robots. TEPCO is continuing to remove radioactive rubble from the plant site using remotely-controlled equipment, and these efforts are reducing radiation levels at the plant.<sup>18</sup>

### **Plans for Recovery and Remediation**

Units 1 through 4 are damaged to the point they cannot return to service. TEPCO is receiving proposals for long-term decommissioning of Units 1 through 4. This work would involve treatment and decontamination of highly active water accumulated in the reactor and turbine buildings, fuel removal, sealing of the reactor vessels to allow activation products to decay, and eventual demolition of the structures. Complete demolition and cleanup may take a decade or more, and will likely cost several billion dollars to complete.<sup>19</sup>

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<sup>14</sup> World Nuclear Association (see Note 8)..

<sup>15</sup> Japan Atomic Industrial Forum (hereinafter referred to as JAIF Status), *Information on Status of Nuclear Power Plants at Fukushima*, April 27, 2011 (available at [http://www.jaif.or.jp/english/news\\_images/pdf/ENGNEWS01\\_1303872153P.pdf](http://www.jaif.or.jp/english/news_images/pdf/ENGNEWS01_1303872153P.pdf))

<sup>16</sup> International Atomic Energy Agency (IAEA), Fukushima Nuclear Accident Update Log, April 26, 2011 (available at <http://iaea.org/newscenter/news/2011/fukushimafull.html>).

<sup>17</sup> World Nuclear Association (see Note 8).

<sup>18</sup> World Nuclear Association (see Note 8).

<sup>19</sup> World Nuclear Association, April 26, 2011 (available at [http://www.world-nuclear.org/info/fukushima\\_accident\\_inf129.html](http://www.world-nuclear.org/info/fukushima_accident_inf129.html)).

On April 17, 2011, TEPCO issued a plan for stabilizing the damaged reactors and beginning long-term mitigation and cleanup. The plan calls for the following actions to be taken during the next six to nine months:

*Reactor shutdown*—in Units 1 and 3, the containment vessels will be flooded up to the level of the top of the fuel, and nitrogen injection will be continued. In Unit 2, the damaged containment building will be sealed with grout and then flooded. New heat exchanger circuits will be built for all three units. The ultimate goal is to achieve “cold shutdown” within six to nine months.

*Cooling and removing spent fuel*—for Units 1-4, water injection into the spent fuel pools in each reactor building will be improved, and cooling water circulation for heat removal will be restored, using new or restored heat exchangers. A support structure will be built under the Unit 4 spent fuel pool, which appears to have experienced the greatest structural damage of all the pools. The fuel in all four pools will eventually be moved to the central storage facility on site (which will need to be expanded).

*Managing contaminated water*—additional storage capacity will be installed, along with a treatment plant to enable recycling. Contaminated water will be treated.

*Minimizing further release of radioactive materials*—dust-suppressing polymer resin will continue to be applied around the facility, and debris removed to improve working conditions on site. A temporary structure will then be built over Units 1, 3, and 4 followed by a more substantial structure later.

### **Actions being taken to review nuclear facility safety in the U.S.**

Several near-term measures have already been taken by the U.S. nuclear industry and the NRC as a result of this disaster. Immediately after the event, reactor operators in the U.S. took a number of actions, including:

- Verifying each plant’s capability to manage major challenges from natural events, fires and explosions. Operators inspected and tested equipment and verified that staff were qualified to operate them;
- Verifying each plant’s ability to manage a total loss of off-site power;
- Verifying the ability of plants to mitigate the consequences of external flooding on systems inside and outside the plants; and
- Performing walk-down inspections of important equipment that would be needed for emergency response.<sup>20</sup>

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<sup>20</sup> Testimony of William Levis, President and COO, PSEG Power LLC, before the Subcommittee on Energy and Water Development, U.S. Senate Committee on Appropriations, March 30, 2011, at p. 5.

On March 18, 2011, the NRC issued Information Notice 2011-05 to its licensees, which was intended to provide a high-level discussion of the events that had occurred at the Fukushima site and to encourage licensee review and consideration of potential actions to avoid similar problems. That Information Notice, available at <http://www.nrc.gov/reading-rm/doc-collections/gen-comm/info-notices/2011/ML110760432.pdf>) referenced earlier Interim Compensatory Measures and related guidelines that were intended to provide mitigation strategies for protecting spent fuel pools in the event of extreme events. That guidance is protected as Official Use Only—Security Related Information (OUO-SRI), and is therefore not available to the public.

The NRC has also launched a two-pronged review of U.S. nuclear power plant safety. The Commission has created a special task force, made up of current senior managers and former NRC experts with relevant experience, to conduct both short- and long-term analysis of the lessons that can be learned from the situation in Japan, and the task force's results will be made public. The NRC has stated it will perform a systematic and methodical review, examining all available information from Japan, to see if there are changes that should be made to its programs and regulations to ensure continued protection of public health and safety. The task force will provide formal updates to the NRC Commissioners on the short-term effort in 30, 60 and 90-day intervals—scheduled for May 12<sup>th</sup>, June 16<sup>th</sup>, and July 19<sup>th</sup>, 2011. The Blue Ribbon Commission meeting on May 13<sup>th</sup> will include a status report on the NRC review.

NRC inspectors who are posted at every U.S. nuclear power plant will also support the task force's short-term effort, supplemented as necessary by experts from the agency's regional and headquarters offices. The task force will help determine if any additional NRC responses, such as orders requiring immediate action by U.S. plants, are called for, prior to completing an in-depth investigation of the information from events in Japan. The longer-term review will identify any permanent NRC regulation changes determined to be necessary. The NRC anticipates the task force will begin the long-term evaluation in no later than 90 days (i.e., by July 2011). The Commission will hold monthly public meetings on NRC's assessment and related actions.<sup>21</sup>

Specifically, the task force will be examining the events at Fukushima Daiichi as more information about what occurred at the reactors and pools becomes available and can be verified. The task force will examine these events in light of current operating practices at U. S. reactors and spent fuel storage installations, including procedures to be followed in case of external events (earthquakes, flooding, hurricanes, tornadoes), station power blackouts and mitigation steps, mitigation of severe (beyond-design basis) accidents, emergency preparedness, and control of combustible gases.<sup>22</sup>

As another part of its longer-term review, the NRC will obtain and verify specific information on the sequence of events at Fukushima and the status of equipment used there. It will evaluate

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<sup>21</sup> NRC Q&A, p. 84.

<sup>22</sup> Presentation by Eric Leeds, U.S. Nuclear Regulatory Commission, April 2011 (available at <http://www.nrc.gov/japan/nrr-fukushima-apr2011.pdf>), p. 10.

potential policy issues and conduct any needed interagency coordination. It will also assess lessons learned for facilities other than operating reactors, and expects to fully coordinate such efforts with key stakeholders. A report will be developed about six months after the start of the longer-term review (approximately January 2012) and will be presented to the full NRC.<sup>23</sup>

At the direction of Secretary Steven Chu, the U.S. Department of Energy's Office of Health, Safety and Security has launched a similar review of DOE nuclear facilities to evaluate facility vulnerabilities to beyond design basis events and to ensure appropriate provisions are in place to address them.<sup>24</sup> DOE facility operators are to review beyond design basis event analyses and mitigation; loss of power event preparedness; safety system operability; and emergency plans, procedures, and equipment. Priority is being given to reviews of the highest hazard category facilities which were to have been completed by April 14, followed lower hazard category facilities by May 13, 2011. The BRC meeting on May 13<sup>th</sup> will include a presentation on the status of DOE's review.

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<sup>23</sup> NRC ACRS Briefing, p. 117.

<sup>24</sup> DOE HHS Safety Bulletin 2011-01, March 23, 2011