APPENDIX G

Status of Spent Fuel in the Unit 1 Through 6 and Common Spent-Fuel Pools at the Fukushima Daiichi Nuclear Power Station

NOTE: Unless otherwise indicated, all dates in this appendix are for 2011.

It is not yet possible to fully develop an unambiguous narrative of what events occurred in the spent-fuel pools (SFPs) at the Fukushima Daiichi nuclear power station (NPS), as significant evidence and information remain to be determined (for example, a detailed examination of the stored used fuel is likely necessary to resolve what happened). Nevertheless, a narrative can be constructed based on the reported observed conditions and relevant analyses to date. There is no doubt that as additional evidence is obtained, the narrative will continue to be refined.

I. BACKGROUND

Each of the six units of the Fukushima Daiichi NPS has its own SFP. In addition, a separate common SFP is used to store fuel that has cooled for a longer time.

Damage to stored used fuel potentially resulting in the release of radioactive material can be the result of

- a sustained loss or degradation of effective active cooling of the SFP water
- loss of SFP inventory
- physical impact of a dropped heavy object
- a combination of the above mechanisms.

The SFP associated with each unit is located on the upper floor of the reactor building in the refueling bay. If alternating-current (AC) power is available, under certain off-normal conditions, an emergency ventilation system provides for filtered release of radioactive material introduced into the refueling bay. The structure surrounding the refueling floor, while inside secondary containment, is not designed for excessive overpressure. In fact, in reaction to a slow overpressure event, blowout panels are designed to open to prevent overpressurization. This protective feature is not designed to limit overpressurization from rapid pressurization, such as might be accompanied with a rapid hydrogen burn or explosion. Opening of the blowout panel or failure of the structure enclosing the reactor bay facilitates establishing a potential path for any radioactive material released from the SFP to the environment.

The common SFP is located more or less at grade level in a building near the Unit 4 reactor building.

The dimensions of a typical SFP used to store used fuel are 50 ft (~15 m) long, 40 ft (~12 m) wide, and 55 to 60 ft (~17 to 18 m) deep (NUREG-1738 [1]). The Fukushima Daiichi Unit 1 SFP is 12 × 10 m (~39 × 33 ft), while the Units 2 through 4 SFPs are 12 × 7 m (~39 × 29 ft); the common SFP is reported to be 12 × 29 m (~33 × 95 ft) [2]. Prior to the earthquake, there was ~7 to 8 m (23 to 26 ft) of water above the tops of the fuel.

Given the complete loss of SFP cooling, the time required to boil off SFP inventory to a critical level depends on several factors, including the initial temperature and volume of the SFP water as well as the amount of heat generated by the used fuel in the SFP. NUREG-1738 provides a conservative (meaning a lower-bound) estimate of the time associated with the loss of SFP inventory due to SFP water heatup and subsequent boiling. That calculation does not consider loss of inventory due to SFP leakage or other loss mechanisms such as excessive "sloshing" in response to an earthquake. The NUREG-1738 calculation estimates that the level of an SFP storing boiling water reactor high-burnup fuel removed from the reactor for 60 days would drop to within 3 ft of the top of the active fuel in 145 hours (~6 days). For fuel that has been removed from the reactor for 1 year, this level is reached in a little more than 10 days. The NUREG-1738 calculation is conservative in part because it assumes that fuel has been removed from both units of a two-unit nuclear power plant, the fuel is high burnup (a greater source of decay heat), and the endpoint of the calculation is when the level reaches 3 ft above the fuel. (The latter assumption may have been necessary to estimate SFP cooling recovery times that would allow operators to locally access the fuel, as the SFP water normally offers significant shielding.) The Committee has not been able to compare the heat load/SFP volume ratio used in NUREG-1738 to those of the Fukushima Daiichi SFPs.

If SFP inventory loss is due only to boiling (i.e., there are no SFP leakage paths), then fuel uncovery does not necessarily mean that the release of radioactive material is inevitable. If the SFP is boiling and only a small portion of the active fuel is uncovered, then steam cooling should be adequate to provide effective cooling. The point is that the time to fuel damage and subsequent release of radioactive material is prolonged.

While conservative, the NUREG-1738 analysis does suggest that in the absence of SFP inventory loss by means other than boiling, the operators of a "typical unit" would have in excess of 6 days to recover effective cooling for fuel that has been in the SFP for 60 days.

II. THE SITUATION AT THE FUKUSHIMA DAIICHI NPS

At the time of the earthquake, each SFP of Units 1 through 6 contained both used fuel and new fuel. The inventories of each SFP are shown in Table 1 along with estimates for March 11 and June 11 of the total decay heat associated with the used fuel.

Table 1
SFP Inventories and Estimated Total Decay Heat

Spent-Fuel Pool	Stored Fuel (Number of Bundles)[a]	Capacity Number of Bundles	Decay Heat (MWt)	
			March 11	June 11
Unit 1	392 (100)	900	0.18	0.16
Unit 2	615 (28)	1240	0.62	0.52
Unit 3	556 (52)	1220	0.54	0.46
Unit 4	1535 (204)	1590	2.26	1.58
Unit 5	994 (48)	1590	1.00	0.76
Unit 6	940 (64)	1770	0.87	0.73
Common	6375 (0)	6840	1.13	1.12

[a] Numbers in parentheses indicate number of bundles of new fuel.

The lack of functioning instruments coupled with high radiation levels preventing access to the SFPs precluded the status of the SFPs or the stored fuel from being directly determined early in the event response. Therefore, the condition of the stored fuel has to be inferred from the available evidence.

II.A. Unit 4

Because of the relatively high decay heat associated with the fuel in the Unit 4 SFP [all fuel had been removed from the Unit 4 reactor pressure vessel (RPV) in December 2010], special concern was focused on this SFP. When the refueling floor containment structure was severely damaged due to an apparent hydrogen explosion early in the morning of March 15, this concern was intensified. Initially, since the RPV was defueled, the source of the hydrogen was thought to be the stored used fuel, implying that the SFP inventory had to have been lost early in the scenario. On March 16, one report [3] speculated that "some leakage from the pool may have been caused by the earthquake." On March 17, another report [4] indicated that workers believed that the Unit 4 SFP was leaking, as the level apparently was lower than could be explained by boiling alone. It is not clear if these statements were made in response to measured SFP temperatures or if they were made in response to the assumption that Unit 4 used fuel was the source of the hydrogen that caused destruction of the Unit 4 reactor building superstructure.

It was determined later in the fall of 2011, that the source of the hydrogen was likely from Unit 3 and a pathway to the Unit 4 refueling floor, likely through a shared vent designed to take contaminants through a filter and then to a stack for an elevated filtered release. The loss of AC power meant that there was no forced flow in this vent system and that contaminants originating in Unit 3 were introduced into the refueling bay of Unit 4.

The level history of the Unit 4 SFP is not yet well known. The SFP temperatures were reported to be 84ºC (183ºF) on March 14 and 15. Water was intermittently sprayed from trucks beginning March 20. Nevertheless, the reported SFP temperature on March 24 was 100ºC (212ºF). Water was introduced to the SFP using concrete pumps starting March 25, which offered a more reliable method of delivering water to the SFP.

Additional evidence of the condition of the used fuel in the Unit 4 SFP was inferred from a series of assessments of specific radionuclides from samples taken of the SFP water. The results of these analyses are summarized in Table 2.

Table 2
Unit 4 SFP Analysis Results

Date of Sample[a]	Sample Size	Results			Comment	Reference
		Isotope	Half-Life	Bq/cm^3		
March 4, 2011	not given	Cesium-134	~2 years	BMDL[b]	Reference measurement	TEPCO Press Release, May 9, 2011 [5]
		Cesium-137	~ 30 years	0.13		
		Iodine-131	~8 days	BMDL		
April 13, 2011[c]		Cesium-134	~2 years	88	First measurement after accident	
		Cesium-137	~30 years	93		
		Iodine-131	~8 days	220		
April 28, 2011	280 ml	Cesium-134	~2 years	49		TEPCO Press Release, May 9, 2011 [5]
		Cesium-137	~30 years	55		
		Iodine-131	~8 days	27		
May 7, 2011	280 ml	Cesium-134	~2 years	56		
		Cesium-137	~30 years	67		
		Iodine-131	~8 days	16		

[a] Samples are taken and then may be measured at a later date.
[b] BMDL = below minimal detection limits.
[c] Date of measurement.

Evaluation of the radiochemical assessments supported the proposition that the source of the hydrogen that led to the destruction of the Unit 4 reactor bay superstructure was Unit 3. However, a companion conclusion made was that some Unit 4 fuel assemblies may have been damaged but that the majority remained intact [3].

A video recording of the Unit 4 SFP was taken on May 8, 2011, and released on May 9 by TEPCO [6]. This video recording did not show evidence of extensive damage. In fact, the fuel racks appeared to be intact with little debris visible in the SFP.

A concern developed centered around the strength of the structure supporting the Unit 4 SFP. Between May 31 and June 20, steel support pillars were installed to provide protection against damage that might result from additional seismic events.

In late September, the temperature in the Unit 4 SFP was <40ºC (104ºF), and a new system to provide active cooling was in operation. Operations were begun to remove the salt from the water that was injected into the SFP before freshwater injection was possible.

II.B. Unit 1

Table 1 shows that the heat load in the Unit 1 SFP is an order of magnitude less than that initially found in Unit 4. The conservative analyses of NUREG-1738 would suggest that loss of Unit 1 SFP inventory through boiling alone would not pose a threat to the stored fuel for several weeks. An explosion damaging the structure housing the Unit 1 refueling bay on March 12 created the opportunity to access the SFP using external sources of water. Beginning on March 31, a concrete pumping truck was used to provide makeup inventory to the Unit 1 SFP.

While the March 12 hydrogen explosion may have caused material to fall into the Unit 1 SFP, there is no evidence that this material caused damage to the stored fuel. If it can be established that the earthquake did not cause significant loss of SFP inventory, it is likely that no damage occurred to the Unit 1 stored fuel. Perhaps in response to the lack of hard evidence of no damage, the September 22 status summary from Japan Atomic Industrial Forum (JAIF), hereafter referred to as the JAIF periodic update, states that the integrity of the fuel in the Unit 1 SFP is "unknown" [7].

An alternative cooling water system has been put in service for Unit 1. As of September, the SFP water in Unit 1 has been maintained at <35ºC (95ºF). Since seawater was not injected into the Unit 1 SFP, there is no need to "desalt" the SFP inventory.

II.C. Unit 2

The decay heat load in the Unit 2 SFP is less than one-third that found in the Unit 4 SFP. This suggests that in the absence of SFP leakage or physical damage to the stored elements from dropped objects, the time associated with damage to fuel elements from boiling caused by loss of SFP inventory is greater than that associated with Unit 4.

The structure surrounding the Unit 2 refueling floor did not experience a hydrogen explosion as did the corresponding structures at Units 1, 3, and 4. However, on March 12, the explosive destruction of the Unit 1 structure resulted in the opening of the protective Unit 2 blowout panel. The relatively limited access afforded by the blowout panel actuation when compared to the failed structures of Units 1, 3, and 4 precluded SFP water makeup options such as use of a concrete pump. Water addition using existing SFP piping began March 20 and was intermittent. By May 31, a dedicated system incorporating a heat exchanger was in service.

While the level history of the Unit 2 SFP is not known at this time, a partial history of measured SFP temperatures has been reported. This history illustrates the observed pattern of heatup and cooling of the SFP. Cooling occurred as a result of the periodic addition of water. As late as April 1, in the absence of the addition of water, the SFP temperature increased some 22ºC (40ºF) in 18 hours. This history is depicted in Fig. 1.

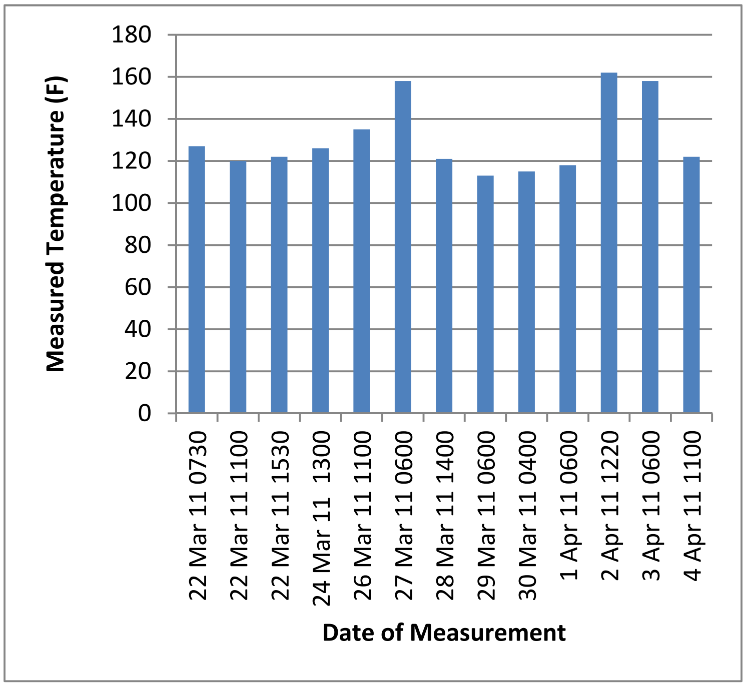

Figure 1. Partial history of measured Unit 2 SFP temperatures.

A sample of the water in the Unit 2 skimmer surge tank was taken on April 16 and analyzed on April 17. The results of that analysis compared to preaccident conditions are shown in Table 3.

Table 3
Unit 2 SFP Analysis Results

Date of Sample	Sample Size	Results			Comment	Reference
		Isotope	Half-Life	Bq/cm^3		
February 10, 2011	not given	Cesium-134	~2 years	BMDL[a]	Reference measurement	TEPCO Press Release, April 18, 2011 [8]
		Cesium-137	~30 years	0.28		
		Iodine-131	~8 days	BMDL		
April 16, 2011	400 ml	Cesium-134	~2 years	160,000	First measurement after accident	
		Cesium-137	~30 years	150,000		
		Iodine-131	~ 8 days	4,100		

[a] BMDL = below minimal detection limits.

If it can be established that the earthquake did not cause significant loss of SFP inventory, it is possible that no damage occurred to the Unit 2 stored fuel. The JAIF periodic update [7] states that the integrity of the fuel in the Unit 2 SFP is "most spent fuel not damaged," citing the analysis of SFP water samples.

As of September, the SFP water in Unit 2 has been maintained at <35ºC (95ºF).

II.D. Unit 3

The decay heat associated with the used fuel in the Unit 3 SFP is approximately one-fourth that of the fuel in the Unit 4 SFP. On March 14, a hydrogen explosion damaged the structure housing the refueling bay. Water spray by water cannon and water drops by helicopter started March 17. By March 27, water addition to the SFP was accomplished by use of a concrete pump. Use of existing SFP piping to restore SFP inventory began in late April.

The SFP water was sampled following the accident with the results summarized in Table 4.

Table 4
Unit 3 SFP Analysis Results

Date of Sample[a]	Sample Size	Results			Comment	Reference
		Isotope	Half-Life	Bq/cm^3		
March 2, 2011[b]	not given	Cesium-134	~2 years	BMDL[c]	Reference measurement	TEPCO Press Release, May 9, 2011 [5]
		Cesium-136	~13 days	BMDL		
		Cesium-137	~30 years	BMDL		
		Iodine-131	~8 days	BMDL		
May 8, 2011	40 ml	Cesium-134	~2 years	140,000		
		Cesium-136	~13 days	1,600		
		Cesium-137	~30 years	150,000		
		Iodine-131	~8 days	11,000		

[a] Samples are taken and then may be measured at a later date.
[b] Date of measurement.
[a] BMDL = below minimal detection limits.

A video recording taken in the Unit 3 SFP on May 10, 2011, and released on June 16 showed debris from the containment structure that had fallen into the SFP [9]. It was not possible to confirm the structural integrity of the fuel racks using the video recording (as determined in the September 2011 report of the Japanese government to the International Atomic Energy Agency, hereafter referred to as the Additional Japanese Government report) [10].

If it can be established that the earthquake did not cause significant loss of SFP inventory, it is possible that no damage occurred to the Unit 3 stored fuel. The JAIF periodic update states that the integrity of the fuel in the Unit 3 SFP is "unknown" [7].

As of September, the SFP water in Unit 3 has been maintained at <35ºC (95ºF).

II.E. Units 5 and 6

The availability of one air-cooled Unit 6 emergency diesel generator throughout the accident prevented significant damage to the fuel stored in the Unit 5 and Unit 6 SFPs. The maximum reported SFP temperature at Unit 5 was 69ºC (156ºF) on March 19. The restoration of forced cooling flow reduced this temperature to 35ºC (95ºF) on March 20. Likewise, the maximum reported SFP temperature at Unit 6 was 67ºC (153ºF) on March 19.

II.F. The Common SFP

Sixty percent of the used fuel at the Fukushima Daiichi NPS is located in the common SFP located near Unit 4. This fuel had cooled for a significant period of time in the unit SFPs before it was moved to the common SFP. The common SFP temperature was reported to have increased to 73ºC (163ºF) by the time the restoration of AC power allowed cooling systems to be placed back into operation.

Radioactive nuclide analysis has been reported for the water found in the common SFP and is summarized in Table 5. Since damage to the fuel in the common SFP is not thought to have occurred, these measurements might be interpreted as a "control" of the sampling process, perhaps reflecting a combination of local contamination from other sources during the accident or during measurement practices.

Table 5
Common SFP Analysis Results

Date of Sample	Sample Size	Results			Comment	Reference
		Isotope	Half-Life	Bq/cm^3		
February 10, 2011	not given	Cesium-134	~2 years	BMDL[a]	Reference measurement	TEPCO Press Release, May 15, 2011 [11]
		Cesium-137	~30 years	BMDL		
		Iodine-131	~8 days	BMDL		
May 13, 2011	1000 ml	Cesium-134	~2 years	0.17		
		Cesium-137	~30 years	1.20		
		Iodine-131	~8 days	BMDL		

[a] BMDL = below minimal detection limits.

III. SUMMARY

The Additional Japanese Government report contained an assessment of the condition of the used fuel stored in each of the SFPs based on available evidence. That summary assessment was expressed in probabilistic terms, reflecting the current incomplete state of knowledge.

For Unit 1, the Additional Japanese Government report concludes "there is a high probability" that exposure of fuel has been avoided by maintaining the water level of the SFPs through the use of a concrete pump and the use of the existing SFP cooling and cleanup system.

For Unit 2, the Additional Japanese Government report concludes "there is a high probability" that exposure of fuel has been avoided by maintaining the water level of the SFPs through the use of the existing SFP cooling and cleanup system.

For Unit 3, the Additional Japanese Government report concludes that the use of the concrete pump and water injection using the existing SFP piping made the avoidance of exposure of fuel "highly likely." Other evidence suggests that damage to the fuel racks cannot be ruled out at this time.

For Unit 4, the Additional Japanese Government report concludes that the damage of some fuel due to falling debris cannot be ruled out. The analysis of SFP water samples is reported to indicate that "most of the fuel inside of the pool appears to be in sound condition and that it is presumed that systematic mass-damage has not occurred."

The available evidence suggests that no damage has occurred to used fuel stored in the Unit 5, Unit 6, or common SFPs.

REFERENCES

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