NRC Overview of the Structural Integrity of the Spent Fuel Pool at Fukushima Dai-ichi, Unit 4

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Purpose

Following the nuclear accident at the Fukushima Dai-ichi nuclear facility in Japan, the U.S. Nuclear Regulatory Commission (NRC) began interactions with the government of Japan that culminated in the formal recognition in December 2012 of a joint steering committee between the NRC and the Japan Nuclear Regulation Authority (NRA). A topic of discussion during meetings of the joint steering committee was the structural analyses performed to confirm the integrity of the spent fuel pool (SFP) within the damaged Unit 4 reactor building at the Fukushima Dai-ichi facility. This report summarizes the NRC staff's assessment of the analyses performed by TEPCO and JNES and the conclusion that the actions taken and analyses performed were reasonable and adequate to address the immediate safety concerns over the structural integrity of the SFP.

Background

The Fukushima Dai-ichi Nuclear Power Plant in Japan consists of five boiling-water reactors (BWRs) with Mark I containment designs and one BWR with a Mark II containment design. Fukushima Dai-ichi began commercial operation in 1971, with the reactors designed by the General Electric Company and operated by the Tokyo Electric Power Company (TEPCO).

On March 11, 2011, a 9.0-magnitude earthquake struck off the coast of Japan and was followed by a 45-foot tsunami, resulting in extensive damage to the nuclear power reactors at the Fukushima Dai-ichi facility. Following the initial damage to the Fukushima Dai-ichi reactors, on March 15, 2011, a hydrogen explosion damaged the fourth floor rooftop area of the reactor building for Fukushima Dai-ichi Unit 4. Because the Unit 4 reactor was shut down and defueled at the time of the earthquake and tsunami, an initial theory for the Unit 4 reactor building damage involved hydrogen gas generation from the Unit 4 SFP caused by a loss of water inventory from the pool and the resultant oxidation of the spent fuel rods' zirconium alloy cladding. It was later confirmed that the Unit 4 SFP structure was intact and the hydrogen explosion was caused by hydrogen leaking from the damaged Unit 3 reactor into the Unit 4 reactor building.

Although there was significant exterior damage to the Unit 4 reactor building, immediate visual observations of the Unit 4 SFP showed that an inventory of water had been and was being maintained to keep the spent fuel adequately cooled. However, as a result of the earthquake and tsunami and the associated loss of electrical power to plant equipment, the SFP lost its cooling systems, and there was concern that the spent fuel would heat the SFP to the point of boiling off the inventory of water. SFP temperatures normally are in the 20-degree Celsius (C) (70-degree Fahrenheit (F)) range. Following the earthquake and tsunami, the Unit 4 SFP temperatures rose to 84 degrees C (180 degrees F) within 3 days of the loss of cooling. At this temperature, it can be expected that evaporative losses would be significant, but with an inventory of almost 400,000 gallons, it would take a long time to reduce the water level to a level which would result in spent fuel being exposed to air. Without addition of water to the SFP for about a week after the earthquake and tsunami, the level of water inventory dropped to 2 meters (7 feet) above the top of the spent fuel assemblies, whereas the normal water levels are about 7 meters (20 feet) above the spent fuel (see Figure 1). Another question was related to the structural integrity of the Unit 4 SFP following the earthquake and hydrogen explosion,

and its ability to withstand additional challenges from significant aftershocks or another major seismic event.

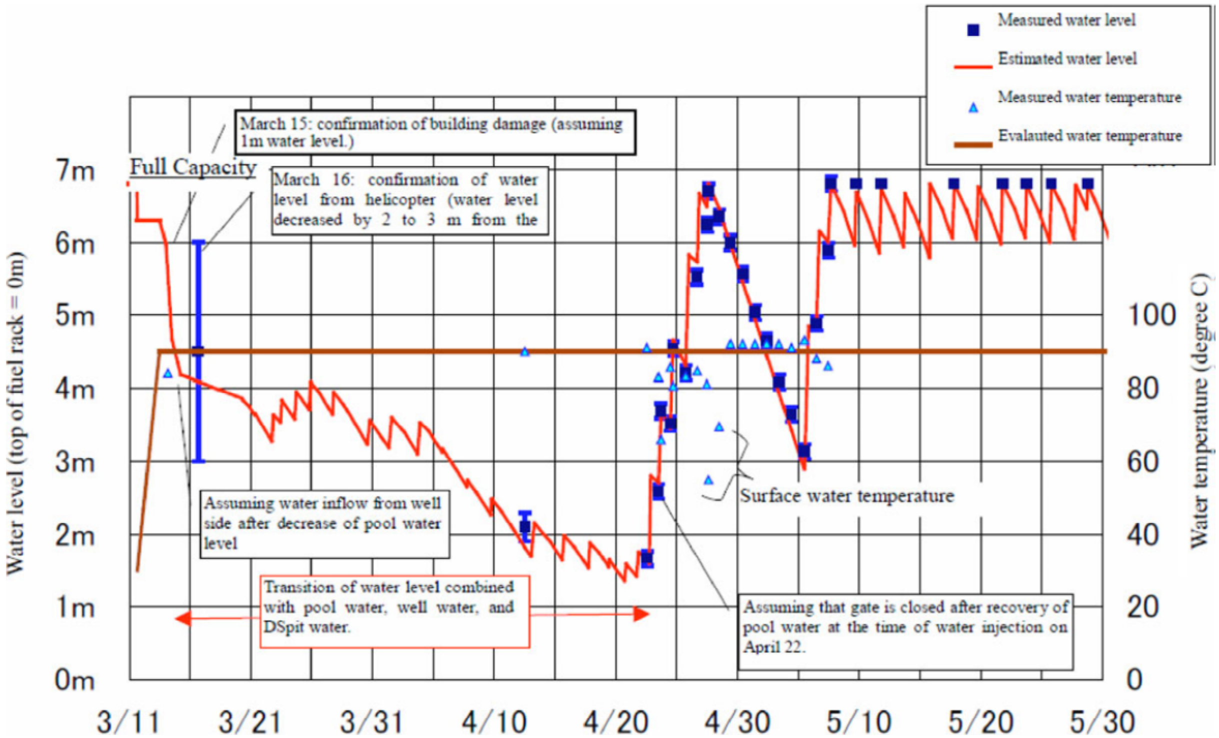

Figure 1: Fukushima Dai-ichi Unit 4 SFP water level (TEPCO)

Within a week of the event, a temporary means of replenishing water was implemented from outside the building by mobile pumps and spraying devices. By June 2011, a permanent water injection and cooling system was implemented. After samples were taken of the SFP water within a month of the event, it was concluded that the spent fuel had not undergone zirconium oxidation or otherwise experienced significant fuel failures during or subsequent to the event.

As concerns about keeping the spent fuel adequately cooled were resolved, attention shifted to the damage done to the Unit 4 reactor building, and in particular the structural stability of the SFP, which is above ground level. With the hydrogen explosion causing unknown structural damage, there were concerns that the Unit 4 reactor building and the SFP might suffer additional damage if significant stresses were applied to the building, such as those that might be introduced by another earthquake. Although much of the roof slab and the sheet metal walls were blown off the building in the hydrogen explosion, this damage appeared to be primarily cosmetic because the underlying structures remained in place. In July 2011, with minimal radiation doses in the lower levels of the Unit 4 reactor building, TEPCO decided to install additional support structures (steel beams with a concrete fill) underneath the Unit 4 SFP to minimize the potential risk of damage to the SFP from subsequent seismic events (see Figure 2).

Within several months of the accident, TEPCO completed the first of several seismic analyses and structural evaluations to confirm the structural integrity of the Unit 4 SFP. The Japan Nuclear Energy Safety Organization (JNES) performed a confirmatory assessment of TEPCO's analyses. Following the completion of these analyses, the Japanese Nuclear Safety

Commission (subsequently the Nuclear Regulation Authority) requested that the NRC assess the analyses and provide possible insights.

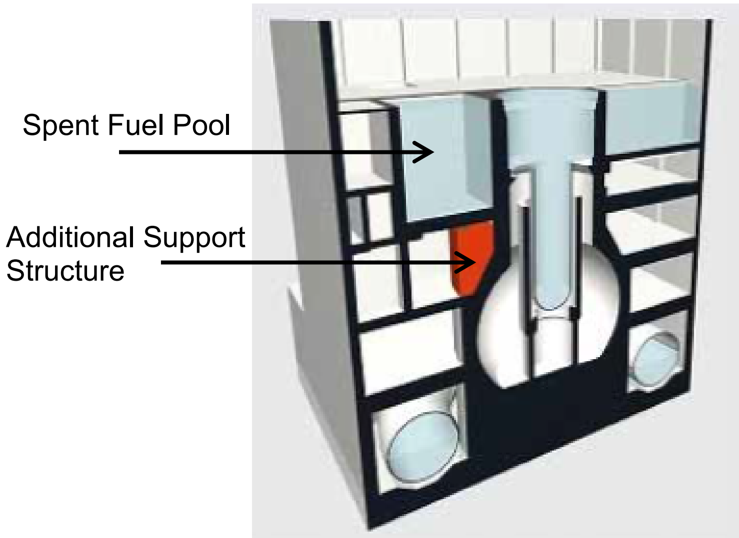

Figure 2: Additional support structure installed beneath Unit 4 SFP (TEPCO)

The NRC closely followed the situation at Fukushima throughout the event through public information and intergovernmental channels. Immediately following the earthquake and tsunami, the NRC began interactions with its Japanese regulatory counterparts and dispatched technical experts to Japan to help at the U.S. Embassy in Tokyo. The NRC assisted the Japanese government and responded to requests from the Japanese regulatory counterparts. The NRC also provided support to the U.S. Ambassador and the U.S. Government assistance effort. As part of these ongoing interactions, the NRC staff reviewed the confirmatory analyses prepared by TEPCO and JNES and offer the following insights.

Spent Fuel Safety Concerns

With the loss of active cooling to the Unit 4 SFP and the unknown damage to the structure, there were concerns that the spent fuel might have been exposed to air, which could lead to a zirconium fire and significant release of radioactive materials. The NRC has conducted several studies to evaluate the risks introduced by SFPs and, specifically, the possible releases of radioactive materials if a breach in the SFP structure were to occur as a result of a severe earthquake. Most recently, the NRC conducted a study (SECY-13-0112, "Consequence Study of a Beyond-Design-Basis Earthquake Affecting the Spent Fuel Pool for a U.S. Mark I Boiling-Water Reactor") for a representative BWR Mark I SFP and found that an earthquake of much larger magnitude than the one that happened at Fukushima had only a small chance of resulting in an SFP leak. This study also showed that a number of additional faults need to occur in order for an SFP accident to result in a release of radioactive material.

The primary barrier to release of radioactive materials from a spent fuel assembly is the cladding surrounding the fuel pellets. As long as the cladding remains in place, the radioactive materials are prevented from being released to the environment. One of the key safety functions for maintaining cladding integrity is ensuring adequate SFP cooling. The spent fuel pellets will continue to produce heat after shutdown through the radioactive decay process. Heat generated by radioactive decay needs to be removed for the cladding to maintain its structural stability and prevent overheating. The standard practice for keeping spent fuel

assemblies cool is to place them in a pool of water that has active heat removal systems. An additional factor to consider with the cooling of spent fuel is the amount of time it has been cooling in the SFP. Starting when the reactor is shut down at the end of each operating cycle, the heat generated by a discharged irradiated fuel assembly decreases as time progresses until a point is reached where it becomes coolable by air if a loss of water inventory were to occur.

In the case of the Fukushima Unit 4 SFP, the most recently discharged spent fuel had been removed from the core approximately 3 months before the event. A study done by the Oak Ridge National Laboratory (ORNL) showed that the recently discharged fuel contributed a significant amount of decay heat to the SFP as depicted in Figure 3. Figure 3 also shows that the amount of decay heat in the Unit 4 SFP between March 11, 2011 and July 29, 2011 steadily decreased since the event. Almost three years after the event, the decay heat remaining in the most recently discharged spent fuel is so low that the spent fuel in the Unit 4 SFP is no longer a threat to catch fire, even if there was a complete loss of water inventory in the SFP.

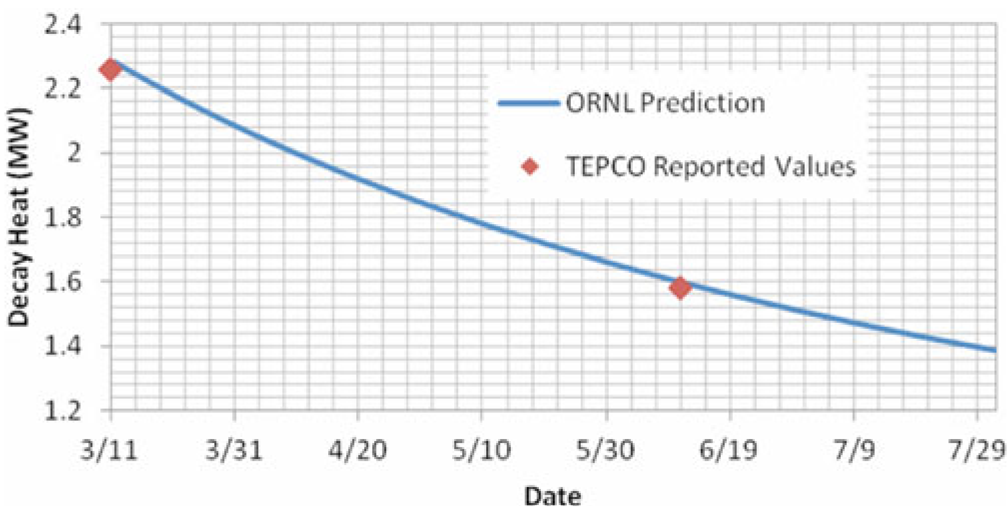

Figure 3: Unit 4 SFP decay heat (ORNL Unit 4 SFP Report, *Nuclear Technology*, November 2012)

It was later determined that the water inventory in the Unit 4 SFP had been kept at a level sufficient to keep the spent fuel cooled. Immediately following the Unit 4 explosion, there were public and international concerns that should the water inventory be lost from the Unit 4 SFP, the recently discharged spent fuel would not be adequately cooled. Because spent fuel can, depending on circumstances, be effectively cooled by water, steam, or air, the likelihood of fuel assemblies overheating to the point of radiological release depends on several factors, including how much residual heat the fuel generates, the fuel loading pattern, and the timing, location, and size of the SFP liner leakage. The NRC SFP study SECY-13-0112 and an assessment by the ORNL provide insights into the ability of the spent fuel to remain cool enough to prevent a release of radioactive materials. The current status of the Unit 4 SFP is that the spent fuel is continuing to be effectively cooled in the pool and the spent fuel assemblies are now being moved to an alternate storage location, and all the spent fuel is planned to be removed from the Unit 4 SFP by the end of 2014.

Structural Analyses Reviewed by the NRC Staff

The NRC staff performed a high-level overview of documents related to the structural evaluation of the Fukushima Unit 4 reactor building and SFP, as they relate to the continued safe storage of spent fuel in the pool during ongoing site-decommissioning activities. The first document is an evaluation performed by TEPCO that was completed in December 2012. The second document was prepared by JNES in February 2013 and contained a cross-check analysis of the results from an earlier seismic evaluation performed by TEPCO. The TEPCO report of December 2012 incorporated some observations and corrections identified by JNES.

TEPCO Structural Evaluation

TEPCO performed analyses of the reactor building and Unit 4 SFP using computational techniques and methodologies consistent with accepted international industry practices for the design and evaluation of nuclear structures and components. The process consists of the following two steps. First, TEPCO performed a seismic time-history response analysis of the entire reactor building to determine seismic boundary loads and deformations. TEPCO then used the results from the seismic analysis, along with other applicable design loads, to support a detailed structural evaluation of the SFP.

TEPCO's primary challenge in conducting its structural evaluation involved developing a realistic reactor building seismic model which accounted for the post-March 2011 structural condition. This evaluation had to account for the earthquake event, hydrogen explosion, and subsequent structural reinforcements made to the reactor building and SFP. The following aspects and features were captured in the seismic model: (1) reduction in mass as a result of removal of rubble at the top of the operating floor and over equipment such as the covers of the containment and reactor pressure vessel, (2) increase in mass resulting from installation of the support frame for the fuel-handling machine, (3) increase in mass associated with the installation of a structure to prevent rainwater from penetrating the area uncovered by the fuel-removal cover, (4) increase in mass resulting from installation of support structures (composed of steel columns encased in concrete wall) on the bottom of the SFP to increase its seismic capacity, (5) the mass associated with soil cover (1-meter (3-foot) depth) added (at time of fuel removal) on the top slab of the first basement floor at the west side of the building, and (6) incorporation of water mass accumulated in the basement floor of the reactor building because of increased groundwater penetration. The NRC staff considers such enhancements of the mass model to be a reasonable representation of the actual structural configuration and appropriate for use in the structural evaluations.

In performing the first step of the analysis, TEPCO's seismic analytical model included certain approximations to reduce the structural stiffness of members affected by the physical damage to the reactor building in areas that were either partially or totally affected by the earthquake. The input seismic ground motions for the Unit 4 reactor building are the basic design S_s-1 and S_s-2 acceleration time histories. The input ground motion is assumed to occur at the free rock surface. The seismic building model is a classic lumped mass stick model of the building composed of elements that account for both bending and shear deformations. The soil-structure interaction is simulated by the use of soil springs. The soil parameters are determined by assuming the ground is horizontally layered; they account for the shear strain caused by an earthquake. Unlike other applications of soil springs in U.S. reactors of the vintage of Fukushima Units 1–4, the soil springs used in this analysis are calculated with refinement that accounts for frequency-dependent complex stiffness. This type of analysis is

used in more recent structural evaluations in the United States and the NRC staff considers it to be appropriate for the subject evaluation of the Unit 4 SFP at Fukushima.

Results from the seismic analysis of the reactor building indicate that the maximum shear strain of 0.16×10^{-3} occurs in a shear wall in the E-W direction on the first floor. This maximum shear strain is considerably lower than the acceptable limit of 4.0×10^{-3}. On the basis of this result, TEPCO concluded that the reactor building, during the removal of spent fuel, has sufficient seismic ruggedness even if the stiffness of the damaged walls is ignored. As such, the analyses by TEPCO concluded that the reactor building is unlikely to collapse in the event of a ground motion equal to the design basis S_s. Given an analytical approach consistent with international practices and the calculated strains being well below acceptable limits, the NRC staff finds this conclusion reasonable.

The second step in the evaluation entailed the performance of detailed structural analysis of the SFP. To accomplish this, TEPCO applied three-dimensional finite element analysis that reflected the actual conditions when the spent fuel is being removed and, as applicable, neglected the structural stiffness of completely or partially damaged sections of the structure. The loading conditions and load combinations included dead load, hydrostatic pressure from pool water, temperature load, seismic load obtained from the earthquake response analysis, and the dynamic water pressure (sloshing) caused by the earthquake ground motion. The NRC staff finds that the TEPCO analyses appropriately addressed the various combinations of loads on the Unit 4 SFP.

TEPCO used the analysis computer code ABAQUS, which is widely recognized and accepted worldwide in the nuclear and aerospace industries because of its vast specialized analytical capabilities. The method of analysis is nonlinear elasto-plastic and it accounted for the plasticization effect in reinforced concrete. To account for elasto-plastic behavior, elements with nonlinear capability were selected. The selected elements were multilayered shell elements with anisotropic material properties to simulate the reinforcing steel layers. In addition to axial and bending moment deformations, the selected elements also account for the effect from out-of-place shear deformations. The NRC staff finds the analysis approach (including the selected computer code) fairly detailed and comprehensive and comparable to what the NRC or U.S. power reactor licensees would perform to address a concern about continued plant operation in light of an identified structural issue.

The evaluation criteria are based on the “Codes for Nuclear Power Generation Facilities – Rules for Concrete Containment Vessel for Nuclear Power Plant” by the Japan Society of Mechanical Engineers, which are similar to the standards in Division 2, “Code for Concrete Reactor Vessels and Containments,” of Section III, “Rules for Construction of Nuclear Facility Components,” of the ASME (formerly the American Society of Mechanical Engineers) Boiler & Pressure Vessel Code. The use of well-established consensus codes and standards is consistent with the regulatory process used by the NRC for U.S. nuclear power plants.

Results from the three-dimensional finite element detailed structural evaluation were provided in the TEPCO report. Calculated stresses and strains were found to be within the elastic limit at every location and sufficiently below the code acceptance limits. On the basis of these results, TEPCO concluded that the seismic safety of the SFP is maintained even when stiffness of the walls and floor slabs at the damaged sections is completely neglected during the condition when the spent fuel is removed. The NRC staff finds this conclusion reasonable in light of TEPCO’s analytical approach, which used a realistic representation of the damaged structures, accepted computational techniques, and well-established acceptance criteria.

JNES Confirmatory Evaluation

JNES stated that the primary objective of its evaluation was twofold. The first objective was to assess the seismic safety evaluation of the Unit 4 reactor building and SFP against a seismic ground motion induced by a future potential earthquake. The JNES assessment took into consideration on-site investigations of the damage to the external walls of the Unit 4 reactor building (including observed localized bulges). JNES's second objective was to review the validity of the three-dimensional finite element model used by TEPCO. JNES used independent analysis codes to evaluate the analytical approximations in the analysis performed by TEPCO. JNES selected specific aspects for further evaluation including the following: (1) the seismic response analysis model, (2) stiffness and strength settings of damaged members, (3) methods for incorporating nonlinear characteristics of members, and (4) calculation of temperature loading.

The JNES analysis focused on the following aspects:

- Three-dimensional behavior: Recognizing that some walls experienced deformation and became irregular while other walls were damaged because of the seismic event, JNES concluded that the behavior and capability of the structure to resist torsion-induced seismic loads needed to be examined. The three-dimensional finite element analysis accounted for identified structural irregularities.

- Nonlinear Characteristics: The analysis takes into consideration nonlinear behavior characteristics of damaged structural members that exhibit cross-sectional deformations and geometric changes from their original shape. The damage level estimated from onsite investigation was used to arrive at a realistic prediction of the properties of damaged cross sections.

- Uncertainties: The analysis takes into consideration three key areas of uncertainties associated with the state of the damaged Unit 4 reactor building structure. First, the analysis includes a reduction of stiffness and strength of members caused by potential damage in regions that might have been affected by the hydrogen explosion, even if these members were judged not to be degraded, based on visual inspections. The primary cause of possible concrete degradation is the pool water temperature, which was not accurately recorded following the explosion. The second uncertainty considered was related to whether or not the rebar axial stiffness effects were small at the cross-sectional center of the pool walls and bottom floor. To address this uncertainty, the analysis conservatively did not consider the increase in axial stiffness effects enhanced by the presence of rebar around the central regions of the cross section of members in setting the nonlinear characteristics of the pool walls and bottom floor. The third uncertainty considered relates to the temperature loading. Typically, differences in temperature gradient through the cross section of thick concrete elements may vary depending on the surface condition and duration. To address this uncertainty, the analysis conservatively ignored the heat-transfer characteristics throughout the concrete thickness and assumed that the temperatures of the wall and bottom surfaces are the same as those of the circumference for setting the temperature loading on the pool walls and bottom floor.

- The JNES evaluation included sensitivity analysis to address parametric variation related to extent of damage level, seismic loading, and temperature stresses. The inclusion of such sensitivity studies is a good engineering practice and is recommended in various NRC guidance documents.

The JNES analysis results reasonably agreed with the analysis performed by TEPCO. The most important item for evaluation in the reactor building was the shear strain in one of the seismic shear walls. The maximum shear strain of the governing seismic wall was calculated at the shell wall on the first floor and found to be approximately 10 percent of the ultimate acceptance limit. The governing parameters selected from the evaluation of the SFP were the concrete compressive strain, rebar tensile strain and the out-of-plane shear force in the pool walls and floor. The governing calculated concrete compressive strain in the pool walls and floor was determined to be 20 percent of ultimate and the rebar tensile strain was calculated to be about 50 percent of the ultimate evaluation limit. The calculated maximum out-of-plane shear force in the pool wall and floor is 80 percent of the evaluation limit. Although the above values calculated by JNES exceed those calculated by TEPCO, the values were nonetheless found to be well within the established acceptance limits.

The NRC staff finds the JNES confirmatory evaluation fairly detailed and comprehensive. JNES used state-of-the-art approaches for this unique evaluation and performed its analyses in ways consistent with recognized engineering practices, codes, and standards. The selected three-dimensional finite element structural model has nonlinear capabilities that enabled evaluation of nonlinear behavior characteristics. The evaluation reasonably captures key aspects of geometric and loading uncertainties and also included sensitivity analysis of significant input parameters.

Conclusion

The NRC staff assessed the TEPCO and JNES analyses of the Fukushima Unit 4 reactor building and SFP. While the JNES analysis used more state-of-the-art techniques, both analyses were performed using well-established and accepted techniques and computer models. Both analyses found that the Fukushima Unit 4 structure would likely survive and maintain the SFP integrity in the event of an additional challenge by a large earthquake in the aftermath of the original seismic event, tsunami, and hydrogen explosions. The NRC staff finds that the analyses and conclusions by both TEPCO and JNES are reasonable given that both organizations developed models to reflect the damaged structures, used widely accepted analytical approaches, and compared the calculated results to well-established acceptance criteria.