Commentary

# Issues on Criticality Safety Control of Fuel Debris

## −Preparation for the Decommissioning of Reactors at the Fukushima Daiichi Nuclear Power Plant−

Kyoto University Research Reactor Institute, **Ken Nakajima**

A technical review was conducted on resolving the issue of criticality safety management for fuel debris to ensure the proper decommissioning of the Fukushima Daiichi Nuclear Power Plant of the Tokyo Electric Power Company. In addition to conducting sufficient examination inside the reactors, consideration must also be given to reducing the overall risks while developing technologies and procedures for removing fuel debris.

## I. Introduction

The Fukushima Daiichi Nuclear Power Plant of the Tokyo Electric Power Company (TEPCO) experienced a core meltdown in all of the three reactors (Units 1–3) that were in operation when an earthquake struck on March 11, 2011. Molten fuel debris is presumed to have not retained inside the pressure vessels, but to have spread inside the primary containment vessels. The Nuclear Emergency Response Headquarters developed Mid-and-Long-Term Roadmap to begin the removal of the fuel debris by the first half of 2020 and complete it within 10 to 15 years (the decommissioning is scheduled to be completed within 30 to 40 years).

There are many technical challenges involved in the removal of fuel debris, such as the criticality safety management technology for fuel debris. This technology monitors the condition of the fuel debris with the aim of maintaining and managing subcriticality at each stage of the decommissioning process to prevent the molten fuel from reaching criticality and thereby leading to the release of a significant amount of radioactive materials. Many studies have been conducted on criticality safety management technology for nuclear fuel materials since the early days of nuclear energy usage. The findings from these studies have been compiled and published in handbooks, standards, databases, and so on. Unfortunately, these studies assumed fuels under normal conditions (including various forms and properties of fuels in reprocessing) rather than the type of fuel debris found at the Fukushima Daiichi Plant. In addition, almost no information has been obtained with respect to the quantity, shape, composition and position of the fuel debris present in each pressure vessel or primary containment

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vessel (PCV). For these reasons, it is necessary to develop technologies for ensuring criticality safety for fuel debris in anticipation of a variety of different situations as well as conduct examinations inside the reactor buildings (R/Bs) and the PCVs.

Issues related to criticality safety management for fuel debris in the decommissioning plan for the Fukushima Daiichi Plant were discussed during the Summer Seminar on reactor physics in 2011 and the planning lecture given by the Reactor Physics Division during the 2013 Fall Meeting of the Atomic Energy Society of Japan [1-3]. Based on these discussions, this commentary explains issues related to critical safety for fuel debris.

# II. Decommissioning

## 1. Conditions at the Fukushima Daiichi Nuclear Power Plant

On December 16, 2011, the Japanese government (Nuclear Emergency Response Headquarters) declared that a “cold shutdown state” had been achieved for the reactors at the Fukushima Daiichi Plant after technically ensuring that the on-site radiation dose could be kept sufficiently low even in the event of any problems [4]. Two years on, cooling by water injection is still being conducted. Meanwhile, examinations of the inside of the reactor buildings (R/Bs) are underway. However, the extent of damage suffered to the fuels has yet to be ascertained.

Any criticality assessment of fuel debris requires data on factors such as its composition, properties, and shape, but we need to make do with estimated data at present. Consequently, the assessment results are greatly influenced by how conservative the estimates are.

Based on TEPCO’s analysis and their plant data, the following fuel conditions are estimated for the respective reactors [5, 6].

Unit 1: Almost all of the molten fuel has dropped to the lower plenum of the reactor pressure vessel (RPV), leaving almost no fuel at the reactor core. Most of the fuel debris that has dropped to the lower plenum is believed to have further dropped to the pedestal of the PCV. Fuel debris triggers a core-concrete interaction, but the fuel debris is believed to remain inside the PCV as the interaction has been stopped by water injection cooling and the subsequent reduction of the decay heat. As of December 2013, the temperature at the bottom of the pressure vessel is being maintained at around 20°C owing to the injection of water through the feedwater system (2.5 $m^3$/h) and the core spray system (2.0 $m^3$/h). The water level of the dry well (D/W) is estimated to be around 2.8 m above the floor, and the suppression chamber (S/C) is estimated to be almost full with water.

Units 2 and 3: Some of the molten fuel is believed to have dropped to the lower plenum of the RPV or the pedestal of the PCV, while the rest is believed to remain in the reactor core. Presently (December 2013), the temperature at the bottom of the pressure vessel is being maintained at around 25°C owing to the injection of water through the feedwater system (1.9–2.0 $m^3$/h) and the core spray system (3.5 $m^3$/h). The water level of the D/W for Unit 2 is about 60 cm above the floor. The water level in the S/C is similar to that of the torus chamber. In Unit 3, the D/W water level is between 5.5 and 7.5 m above the floor, but the water level in the S/C is unknown.

## 2. Mid-and-Long-Term Roadmap

In December 2011, the Japanese government and TEPCO drew up Mid-and-Long-Term Roadmap for decommissioning of the Fukushima Daiichi Plant (revised in July 2012 and June 2013) [7]. **Figure 1** provides an outline of this Roadmap. The main objective of the decommissioning is to minimize the impact of radioactive materials for outside of the site and reduce the exposure to the pre-disaster level. To this end, the following goals were set in the Roadmap to ensure safety.

(1) Complete the decommissioning as soon as possible while maintaining safe conditions at the plant.

(2) Ensure safety beyond the site (reduce exposure on the public).

(3) Ensure safety at the site (reduce exposure on workers).

The Roadmap is divided into three phases. Phase 1 begins with the completion of Step 2 [a] and ends with the removal of fuel from the spent fuel pool for the first Unit undertaken. This phase was completed in November 2013. Phase 2 corresponds to the period up to the removal of fuel debris from the first Unit undertaken. In this phase, the necessary research and development is initiated along with the repair work for the PCV, stagnant water treatment is completed, and research and development into dismantling the facility and treating and disposing waste is initiated (the initial completion target is 10 years after the completion of Step 2, but a revision to the roadmap shifted the target to the first half of 2020). Phase 3 is scheduled to last until the completion of the decommissioning. Removal of the fuel debris is to be completed within 20 to 25 years from the completion of Step 2, while the decommissioning is to be completed within 30 to 40 years.

The removal of fuel debris is supposed to be performed according to the following steps.

(a) Decontamination inside the reactor buildings (R/Bs)

(b) Repair of R/Bs and PCVs to terminate the water leakage as well as switch from cooling through the use of a large circulation loop to cooling through the use of a circulation loop inside each building and, ultimately, to cooling through the use of small circulation loops [b]

(c) Examination and sampling inside PCVs

(d) Filling with water and opening of the top covers for the pressure vessels

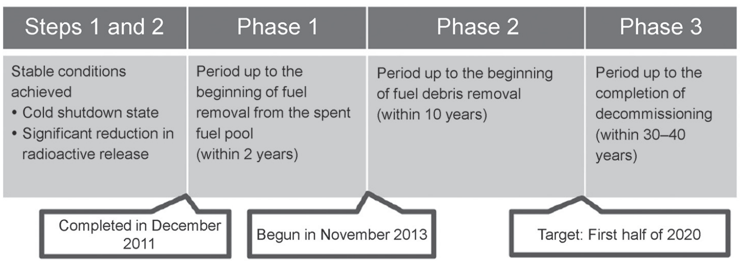



**Figure 1** Outline of Mid-and-Long-Term Roadmap

[a] One of the steps deemed necessary to remedy the Fukushima accident by bringing the release of radioactive materials under control and significantly reducing the radiation dose rate (cold shutdown state). This condition was achieved in December 2011.

[b] Large circulation loops: loops currently used for circulation. Circulation loops inside buildings: loops used to bypass the equipment that is currently being used for the treatment of contaminated water to inject stagnant water inside the buildings into the reactors. Small circulation loops: loops that circulate water inside the PCVs after the water leakage has been terminated inside them. Details of changes to the loops are determined according to how the water leakage is terminated and how the infiltration of ground water is prevented.

(e) Examination and sampling inside reactors
(f) Removal, transport, and storage of fuel debris

Adequate measures must be taken to prevent criticality by assessing the impact that each step has on the criticality safety management for fuel debris.

In Step (b), an alternative method of removing fuel debris without filling with water is considered if the water leakage cannot be terminated. In this case, the possibility of criticality can be considered almost negligible in the absence of water as a moderator. If a shielding material is used, its neutron reflection and moderation effects need to be taken into consideration.

# III. Challenges Involving Critical Safety

## 1. Approach to Criticality Assessment

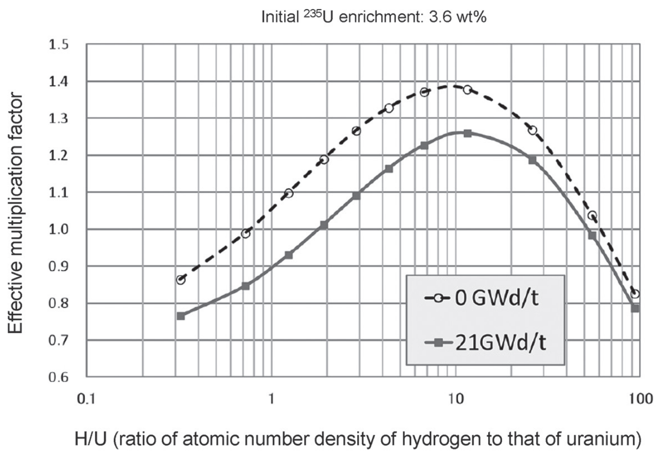
One of the goals set under the Mid-and-Long-Term Roadmap is quick completion of the decommissioning process while always ensuring safety. The quick completion of this process is intended to reduce the risk posed by a failure of the due containment function at the Fukushima Daiichi Plant quickly even though stable conditions have been achieved. Obviously, the top priority in criticality safety management during the removal of fuel debris is to prevent any criticality events having a significant impact on the public, workers, and the environment. In addition, the removal must be performed and completed as early as possible.

The key to achieving this is to conduct the work efficiently while ensuring safety based on realistic assumptions that reflect the actual conditions at the site. Criticality should also be assessed by using the best estimate based on actual conditions rather than excessively conservative conditions that go beyond the realistic settings used in ordinary safety assessments. To this end, the possible range of change (error) must be assessed for the estimated results. Realistic assessments require information related to the fuel debris, such as its composition, density, and distribution. If any missing information must be replaced with estimates, conservative settings must be applied while taking into account estimation errors. For this reason, examinations must be conducted inside the PCVs and reactor pressure vessels as soon as possible.

## 2. Assessment of the Possibility of Criticality

### (1) Assessment of Criticality

The composition of fuel can be assessed based on operational management data, such as the operational history of each reactor. If we assume that the composition of the fuel debris is homogenous, its composition can also be assessed. However, analysis of the fuel debris from TMI-2 indicates that the composition is influenced considerably by the way the fuel melts. For this reason, a homogenous composition of the fuel debris is only hypothetical. Nonetheless, criticality was assessed based on a homogenous fuel of the Fukushima Daiichi Plant to determine what condition would cause the fuel to reach criticality. **Figure 2** presents the H/U dependency of the effective multiplication factor for a spherical core with a homogenous distribution of $UO_2$ powder in water ($H_2O$) and a burnup of 21 GWd/t as well as the dependency of fresh fuel (0 GWd/t). This example assumes an initial amount of uranium of roughly 100 tons in an assembly of 548 fuel assemblies that have been loaded in both Units 2 and 3, and it can be considered as an almost infinite system. The burnup of 21 GWd/t simulates the average burnup of 21.8 GWd/t in Unit 3. The H/U on the figure’s horizontal axis is the ratio of the




| H/U | 0.7 | 2.0 | 10 | 50 | 60 |
|---|---|---|---|---|---|
| U cconcentration (gU/liter) | 7700 | 5600 | 2000 | 500 | 420 |
| Water content (Vol%) | 20 | 42 | 79 | 95 | 96 |

**Figure 2** H/U dependency of the effective multiplication factor for $UO_2$ fuel [2)]

atomic number density of hydrogen to that of uranium, which represents the degree of neutron moderation. The table below the figure presents the uranium concentration and water content corresponding to typical H/U ratios. In the assessment of the effective multiplication factor for burned fuel, FP nuclides were applied in the manner accepted for the assessment of burnup credit in accordance with the Criticality Safety Handbook [8)]. Structural materials and control rods ($B_4C$) were assumed to be absent.

Figure 2 indicates that an H/U ratio of around 10 achieves the optimal moderation for both the burned fuel and the fresh fuel, so it gives the largest effective multiplication factor. Criticality was reached for the burned fuel with an H/U ratio in the range of 2.0 to 50 and for the fresh fuel with an H/U ratio in the range of 0.7 to 60. These ranges correspond to a uranium concentration of between 400 and 7,700 gU/L, which is quite a dense uranium solution. Such a condition may be produced in a transient manner, such as in a case where fuel debris in a powder form is agitated by cooling water. In terms of the volume ratio (water content), criticality can be reached within a wide range of between 20 and 96%. The infiltration of water into pores of fuel debris could lead to criticality being reached. Burned fuel in the optimal moderation condition reaches criticality with about 300 kg of uranium [c]. However, this assessment does not take into account structural materials, absorbers, and impurities or other substances in water. It assumes that the fuel has the spherical shape that most easily reaches criticality. Although this is hypothetical, it should be noted that a critical mass of just 0.3% of the loaded fuel in the reactor (ca. 100 tons) could trigger criticality.

**(2) Possibility of criticality during cooldown**

As was explained earlier, most of the fuel in Unit 1 is assumed to have dropped to the pedestal of the PCV with almost none remaining in the core. In contrast, some of the fuel is assumed to have remained in the core regions of Units 2 and 3, with the rest having dropped to the bottom of the pressure vessels or the pedestals of the PCVs. Cooling water is injected

[c] Figure 2 indicates that the effective multiplication factor at the optimal moderation is about 1.28. This value was treated as the infinite multiplication factor for determining the radius of a sphere that causes criticality. Assuming that the migration area $M^2$ is 33 $cm^2$, the geometric buckling of a spherical reactor resulted in a radius of about 34 cm and 330 kg of uranium.

using the feedwater systems and core spray systems. Each feedwater system injects water into the bottom of the reactor pressure vessel through the outside of the shroud. The core spray system injects water directly into the core region. However, a significant amount of cooling water is not expected to be present in the core region because the pressure vessel in each reactor has been damaged. The water level inside the PCV varies for each reactor (see section II. 1), which reflects the extent of damage sustained by each PCV.

Units 1 to 3 are equipped with PCV gas management systems [9)] that are designed to remove airborne radioactive materials to minimize their external release and to monitor the hydrogen gas concentration. These gas management systems are employed simultaneously to monitor the criticality of fuel debris. By measuring Xe-135 as a fission product [d], these systems classify any Xe-135 concentration that exceeds 1 $Bq/cm^3$ (about 100 times the Xe-135 concentration produced by the spontaneous fission of Cm-244, etc.) as criticality. This threshold amounts to an output of around 10 W. Criticality is also determined based on changes in the temperature of a reactor pressure vessel and the air dose rate at each monitoring post. No criticality has been identified to date, so it can be concluded that no significant criticality has taken place. In response to any sign of criticality, a boric-acid solution is to be injected through the injection systems.

The Fukushima Daiichi Plant has experienced many earthquakes (aftershocks) and changes in the volume of cooling water since the cold shutdown state was announced. It can be assumed that the future risk of criticality is extremely low given that these events are not believed to have caused any significant changes in the criticality. However, adequate monitoring is required if there is a possibility of events occurring that may change the distribution and shape of the fuel debris.

**(3) Possibility of criticality during removal**

Water is supplied after the PCVs have been repaired and the water leakage has been terminated in preparation for the removal of fuel debris. This operation floods areas that have not previously been exposed to water, could trigger criticality. However, given that criticality is approached based on the speed of the water injection, signs of criticality can reasonably be detected by adequate monitoring. Assuming a moderate reactivity increase, even if the operation results in criticality (or excess criticality), measures to stop any further reactivity insertion can be taken by detecting such a development before the reaction has advanced too much. If a large amount of fuel debris may move while the water is being supplied, similar measures to those taken for the removal of fuel debris, described below, must be introduced.

The possibility of criticality is at its greatest during the sampling and full-scale removal of fuel debris after the water has been supplied because the shapes and positions of the fuel debris are changed directly. A relatively large rise in reactivity can be expected to occur in a short period of time if a large amount of fuel debris collapses or falls down during the removal process and piles up in the bottom of the pressure vessels and/or on the pedestals of the PCVs. Therefore, before the removal process begins, necessary measures must be implemented by adequately checking the condition of the fuel debris. Depending on the circumstances, it may be necessary to mix a neutron absorber [e] into the system.

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[d] Xe-135 is mainly produced by the decay of I-135 with a half-life of 6.6 hours, which causes a time delay in any changes in the concentration. For this reason, an alternative system is being developed to enhance the response speed by switching the detected nuclide from Xe-135 to Kr-87 and Kr-88.

[e] It is evaluated that the full injection of a boric-acid solution into the PCV would require about 200 tons of boric acid. The other problems that also exist include equipment corrosion and waste liquid treatment. For these reasons, the use of neutron absorbers in pellet or gel form has been proposed to facilitate criticality safety management during the fuel debris removal (2013 Spring Meeting of the Atomic Energy Society of Japan, H34).

## 3. Criticality Events

Any criticality of the fuel debris may potentially affect workers and the public through exposure to radiation as well as the public and the environment through the release of gaseous radioactive materials.

Fuel debris is present in the reactor pressure vessels or the PCVs. The removal of fuel debris in such a high-dose radiation field is mainly conducted remotely. The impact of radiation exposure on workers and the public is most likely minute because any criticality involving radiation would occur inside adequate shielding. Additional shielding must be installed along with the implementation of other necessary measures in case the fuel debris may reach criticality outside of a PCV.

The impact that the release of gaseous radioactive materials may have on the surrounding environment depends on the magnitude of criticality (power and duration). If any criticality remains low, the impact on the surrounding environment is also minor. In principle, it is desirable to avoid any criticality. However, the overall risks do not change if any criticality has only a negligible impact on the surrounding environment. It must be noted that any overly complex and lengthy procedure for preventing criticality can actually result in even higher overall risks.

TEPCO has assessed the dose rate from exposure to the noble gases and iodine produced during criticality. The estimated exposure dose rate is 24 μSv around the site if criticality with the power of 1 kW lasts for 24 hours (24 kWh)[10]. Thus, the power of 100 kW for 10 hours (1,000 kWh) would result in a dose rate of 1 mSv. These estimates ignore the normal containment function, so they will be lower if containment function is taken into account. For this reason, the impact that any criticality has on the surrounding environment can be kept low if it is detected early enough and brought under control quickly. To this end, a technology must be established for the early detection of any signs of imminent or actual criticality and adequate shut measures must be introduced to enable the situation to be brought under control quickly.

If the reactivity surges due to the relocation of a large amount of fuel debris, a significant number of nuclear fissions may take place before criticality is detected and a shut measure is initiated, thereby leading to the release of a large amount of gaseous radioactive materials. The magnitude of criticality depends on the added reactivity. Mechanically unrestrained fuel debris can be returned to subcriticality in a relatively short time as its shape changes due to the mechanical energy release associated with a rapid power increase. Heat can easily transfer from the fuel debris into the water through the large surface area. Therefore, a major steam explosion that may damage the reactor pressure vessels or the PCVs is unlikely. Nonetheless, the condition of the fuel debris must be examined before any work that involves a change in the shape of the fuel debris is conducted in order to take necessary measures against rapid reactivity insertion.

# IV. Future Tasks

The following tasks must be considered in line with the discussions conducted to date with respect to criticality safety management during fuel debris removal.

− Ascertainment of the current condition

Clarify the composition, density, and location of fuel debris. The required tasks include clarification of the melting process using analysis codes and so on, examination of the inside of the reactors, and sampling and analysis of samples.

－Validation of the critical assessment

Confirm the validity of the accuracy (errors) of the critical assessment based on the above-mentioned understanding of the current condition.

－Detection of criticality and implementation of shut measures

Develop an early detection system for identifying signs or actual evidence of criticality and a system for quickly returning any detected criticality to subcriticality. Confirm the effectiveness of these systems in terms of their ability to detect and stop criticality.

－Evaluation of overall risks

Extract risk factors for the removal of fuel debris, including those involved in criticality safety management. Evaluate the overall risks in various scenarios and consider measures for reducing these risks to ensure the safety of the public and workers and protect the environment. The implementation of these measures requires the disclosure of information to gain the understanding of stakeholders.

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