APPENDIX C

Accident Cleanup

NOTE: All sections in this appendix relate to the Fukushima Daiichi nuclear power station.

I. CHALLENGES TO WATER CLEANUP ON-SITE

I.A. Challenges and Current Conditions

The Fukushima Daiichi accident produced and is still generating growing volumes of liquid waste that needs to be managed and cleaned up. From the onset of the crisis, the dissipation of the decay heat via the addition of water has resulted in runoff and accumulation of water in lower elevations throughout the site, as well as waste deposition into the ocean. During later phases and up to the present, management of the accumulated contaminated liquid effluents in enclosed areas (basements and tanks, etc.) and partially enclosed areas (e.g., walled, oceanside regions) has been such a challenge that it has impacted the response and recovery efforts. On-site interim storage of liquid-holding (waste) tanks is steadily increasing and will pose additional operational limitations in months to come. A projected volumetric analysis of anticipated needs regarding empty and filled tanks is not known to be publically available [Tokyo Electric Power Company (TEPCO) publishes this information on a regular basis—see the TEPCO latest road map for the most recent information: http://www.tepco.co.jp/en/nu/fukushima-np/index-e.html].

Thus, there are the following challenges:

1. effective management of highly contaminated water, with ~30 tons generated daily for some time to come

2. limited on-site storage space for storage of water (containers may be clean, empty, contaminated, or tritiated). Cleanup capacity of contaminated streams—e.g., those laden with ions, oil, and salt—is limited, and thus, recycled water remains a small fraction of total water inventory needed in the cleanup.

3. treatment of secondary waste produced from cleanup activities using both systems (i.e., AREVA-Kurion and Toshiba-SARRY). Both systems produce large amounts of highly radioactive solid materials (e.g., loaded zeolite, various sludges, filter media, etc.) that must be stored in vessels, shielded, stored in the interim, treated if necessary, and managed until an ultimate disposal path is selected. As of December 2011, 581 m^3 of sludge has been produced from the AREVA system, which is no longer being used, and 275 vessels have been depleted—22 from Toshiba-SARRY and 253 from AREVA-Kurion. Approximately four waste vessels are currently being produced per week. The site can presently store 800 m^3 of sludge and 393 waste vessels.

4. effective management, extraction, storage, and treatment of contaminants stratified in the nearby walled, oceanside regions

5. guidance, monitoring, and management of off-site liquid effluent streams due to weathering over the fall and winter months, and that generated by grassroots cleanup efforts. City sludge and runoff treatment, as well as collected pools of water, will need to be monitored and assessed. This factor cannot be neglected because of risk significance and communication impacts.

6. freeze protection during the winter, which is a concern for portions of water treatment and cooling injection systems that are not currently operating. Only two of the six water injection pumps are operating. Freezing pumps, hoses, or resins could cause leaks and damage equipment.

I.B. Recommendations

1. Continued on-site storage of containerized liquid waste streams is a good interim practice but should be integrated and managed along with the solid debris. Routine inspections should be conducted to ensure durability of containers (corrosion, damage). A means to contain leaks is needed.

2. Assessment, planning, and implementation of postinterim storage processes for containerized waste and debris are needed. Developing a risk-informed end state for the various types of low-level waste (LLW) to be dealt with should be considered. This acceptable end state would not only drive the characterization, treatment, and encapsulation options for the various waste streams, but it would also impact the disposal facility design and closure requirements, allowing acceptable performance requirements to be met. Anticipated construction of an on-site or near-on-site waste treatment facility is needed. This may be in the form of near-surface trenches.

3. Cleanup of contaminated streams—i.e., those that are laden with ions, oil, and salt—needs to continue, but alternative means should be considered such that interim storage in near-surface trenches is an option prior to availability of more permanent storage.

4. Development of a multiuse storage and disposal facility (possible on or near the Fukushima Daiichi site) for a variety of LLW types, including debris, contaminated environmental media, secondary waste from water treatment activities, and operational LLW, should be considered.

5. Guidance, monitoring, and management of off-site liquid effluent streams due to weathering and those generated by grassroots cleanup efforts should be planned and implemented. City sludge and runoff treatment, as well as collected pools of water, will need to be monitored, assessed, and possibly included in the cleanup. This task should be considered part of the risk communication responsibility.

6. Freeze protection during the winter should be implemented for those portions of the water treatment and cooling injection systems that are not currently operating. Building of enclosures or heat tracing can prevent freezing of pumps, hoses, or resins that could cause leaks and damage equipment.

II. RADIOACTIVE WASTE MANAGEMENT AT FUKUSHIMA DAIICHI

NOTE: Some information in Sec. II comes from the following sources:

L. H. Barrett, "Energy, Air, Water & Earth: Fukushima & Three Mile Island: Accident, Recovery & Challenges," presented at Emergency Management Conference, Harrisburg, Pennsylvania, September 26–28, 2011.

H. Ishizuka and H. Mori, "Estimated 13,000 square km Eligible for Decontamination," *Asahi Shimbun*, October 12, 2011; http://www.asahi.com/english/TKY201110110214.html.

Planning for cleanup and waste management of the Fukushima Daiichi site to date is very open-ended. Some critical questions are: Does one limit the scope to the cleanup and waste management of the Fukushima Daiichi nuclear power plant (NPP) site itself, or should contamination that spread beyond the site boundary be included? Where is the line between speculative questions and the most likely next steps when plans for cleanup (other than the "cover" TEPCO is building) have not been announced? In other words, what are the goals for the activities that compose the cleanup efforts, and what are the clear measures of success?

II.A. Challenges

II.A.1. Radioactive Contamination Off-Site

Japan's current situation with widespread radioactive contamination in the environment because of an accident at a commercial nuclear facility is not unique. The accident at Chernobyl in 1986 made a large area of land surrounding the facility uninhabitable. However, Japan's challenge is politically and emotionally more complex because of its being the only country in the world to have been struck by nuclear weaponry during wartime. While the initiating reasons for widespread radioactive contamination are vastly different from Chernobyl, Japan's citizens may view the contamination spread from the Fukushima Daiichi site as yet another "nuclear attack" upon their way of life, upon their children, and upon their very well-being. For this reason alone, confidence in the peaceful uses of nuclear technology can only be restored with an aggressive program to remediate contamination at and beyond the Fukushima Daiichi site, to the extent practicable and with agreement from all stakeholders involved.

Returning people to their homes and restoring the way of life the affected citizens enjoyed prior to the events at Fukushima Daiichi must be a primary focus once the NPPs are deemed stable. This effort must be performed in parallel with placing spent fuel from the damaged spent-fuel pools (SFPs) in Units 1 through 4 in dry storage, and with removal of the damaged reactor cores. The long-term goal for the site should be release of the site for industrial use and for long-term storage of spent nuclear fuel and highly radioactive core components—until a suitable facility for reprocessing and/or disposal of this material can be developed.

II.A.2. The SFPs at Units 1 Through 4

The major earthquake experienced at the Fukushima Daiichi site caused potential damage to the spent fuel and SFPs at Units 1 through 4. Primary damage to the SFPs—damage as a direct result of the earthquake—can be speculated, but direct evidence has not yet been established. Secondary damage—the result of building debris falling into the SFPs due to the hydrogen explosions at Units 1, 3, and 4—is very clear from aerial photography. Additionally, one wall of the SFP at Unit 4 has partially collapsed, leaving only the liner in place to maintain the water inventory of the SFP. It is not clear whether the damage to the SFP in Unit 4 is a direct result of the earthquake or is due to the explosion experienced later in the accident sequence. As a result of the damage, additional metal supports and concrete have been added to support the Unit 4 SFP.

In any case, the SFPs no longer represent a safe environment for the long-term storage of spent nuclear fuel. Recovery of the site must include an early focus on moving spent fuel out of the SFPs and into dry-storage systems, which are capable of being moved off-site at some later time.

II.A.3. The Reactor Cores at Units 1, 2, and 3

The reactor cores at Fukushima Daiichi Units 1, 2, and 3 experienced extensive damage. The remaining debris will need to be contained in the near term, to prevent further contamination of the environment on-site and off-site.

II.B. Current and Future Conditions

II.B.1. Radioactive Contamination Off-Site

The Japanese newspaper *Asahi Shimbun* estimates that the central government will be responsible for decontaminating ~5,000 square miles in eight prefectures—roughly 3% of Japan's total land area. This estimate is based upon a policy endorsed by the Japanese Ministry of the Environment on October 10, 2011. The policy stipulates that all areas of radioactive contamination with >100 mRem/year be remediated to below that level.

The Ministry noted that ~700 square miles in Fukushima Prefecture exhibit contamination levels >500 mRem/year, with no contaminated areas outside Fukushima Prefecture in excess of 500 mRem/year. An additional 2,400 square miles in Fukushima Prefecture show contamination levels between 100 and 500 mRem/year, as do 1,900 square miles in seven other prefectures: Gunma, Tochigi, Miyagi, Ibaraki, Chiba, Tokyo, and Saitama.

II.B.2. The SFPs at Units 1 Through 4

NOTE: The following analysis of the current status of the SFPs at Units 1 through 4 is based upon interpretation of the limited amount of available data.

Radiochemistry data for the isotope contamination [iodine-131 (^{131}I), cesium-134, cesium-136, and cesium-137 (^{137}Cs)] in the SFPs at Units 1 through 4 have been made available by TEPCO. Beginning with Units 1 and 3, which experienced hydrogen explosions and debris falling into the SFPs, the radiochemistry data indicate an elevated presence of both radioactive iodine and radioactive cesium. The presence of ^{131}I in these two SFPs indicates "crossover" contamination from the reactor cores, because otherwise there would be no ^{131}I detectable from the aged spent fuel residing in the SFPs at these units. However, the elevated levels of radioactive cesium lend credence to the conclusion that some spent fuel in these SFPs was damaged by falling debris, with the resultant release of radioactive cesium from the gap region of some of the fuel elements.

In Unit 4, only very low levels of contamination have been detected. Given the ratio of radioactive iodine to radioactive cesium in the radiochemistry analysis, a conclusion can be reached that contamination of the SFP water at Unit 4 is not due to damage to the spent fuel contained within. It now appears that the Unit 4 SFP radioactive contamination may be due to crossover contamination from the other three units. Given the physical damage to the building structure, physical damage to the spent fuel residing in the SFP should not be ruled out, but it can be reasonably concluded that there is minimal damage to the fuel in this SFP.

The status of spent fuel in the Unit 2 SFP remains more uncertain. As Unit 2 did not experience a hydrogen explosion and subsequent building collapse, a conclusion that spent fuel in this SFP was damaged due to falling debris cannot be drawn. It is now postulated that fuel in the Unit 2 SFP became uncovered, overheated, and subsequently experienced cladding failures before TEPCO was able to restore water level. However, since only a limited set of radioactive species were reported by TEPCO, it cannot be determined whether fuel overheated and cladding failed, or if rapid oxidation of the cladding took place. Given the levels of contamination in the water, the latter is considered to be unlikely or, at worst, very limited.

As of December 2011, TEPCO has managed to restore SFP closed cooling and is able to monitor SFP water levels. While this achievement is remarkable given the magnitude of the accident, the SFPs remain a priority risk. The proper option going forward is to remove spent fuel from the SFPs at Units 1 through 4 and place it in dry storage or in the common SFP on-site as fuel is removed from that SFP into dry storage.

II.B.3. The Reactor Cores at Units 1, 2, and 3

Similar to the core at Three Mile Island Unit 2 (TMI-2), the remaining debris at Fukushima Daiichi will need to be remotely segmented and placed into dry storage along with spent nuclear fuel. This effort is likely to be the critical path to the site remediation project and will require extensive planning and precise execution.

II.C. Recommendations

1. The Japanese Ministry of the Environment has established reasonable and achievable guidelines for radioactive contamination remediation off-site. The process of reducing off-site contamination levels to <100 mRem/year—a level that is in line with the impact of an operating nuclear facility to off-site residents—provides assurance to all stakeholders that environmental safety remains a first-order principle in nuclear operations.

2. Spent nuclear fuel should be moved from the SFPs at Units 1 through 4 as soon as practicable. Priority should be given to moving intact spent fuel in the common SFP into dry storage to make room in the common SFP for fuel from Units 1 through 4 if the fuel integrity can be proven. Otherwise, failed fuel must conservatively be stored in the dry-storage cask designed for failed fuel. The common SFP may then be used to handle, examine, and segregate damaged fuel and to prepare for dry storage of the spent fuel currently residing in the SFPs of Units 1 through 4. Dry-cask storage should be envisioned as being long-term, but with the express commitment to transport spent fuel from the Fukushima Daiichi site when the infrastructure becomes available to do so.

3. Consideration should be given to using the common SFP for segmenting and packaging reactor debris and core internals. Once operations for removing spent fuel and placing it into dry storage are complete, utilizing this facility to assist in properly sizing debris for disposal from Units 1, 2, and 3 may prove useful. This will allow large pieces of debris to be removed in well-shielded casks from the damaged units and should facilitate a more rapid cleanup of the reactor buildings.

4. The nuclear community in the United States must remain fully supportive of Japan's efforts to return the Fukushima Daiichi site to industrial use and the associated cleanup of the environs surrounding the site. The ability to restore the lifestyle of residents impacted by the events at Fukushima Daiichi is global; how this restoration is performed will reflect upon other nuclear-energy-generating operations throughout the world.

III. FUTURE PLANS

What are the plans beyond those previously announced by TEPCO to take place over the next 6 to 9 months of 2012? When will plans for cleanup of the Fukushima Daiichi site be announced?
At this time TEPCO has focused only on stabilization and cold shutdown of the reactors and SFPs. The mid-term to long-term plans have not yet been developed. The sense of urgency in sealing the containment and removing the fuel from the SFPs has not received the priority that it deserves. There are financial and political barriers to establishing the entire plan in such a way that all parties can reach consensus regarding the desired outcomes. There is no timeline or vision for the future of the site. The U.S. Department of Energy conducted a workshop in Japan in October 2011 to establish the focus for the site cleanup. Two Japanese consortiums (Toshiba and Hitachi) have prepared presentations and provided them to TEPCO. However, steps I and II of the TEPCO road map (http://www.tepco.co.jp/en/nu/fukushima-np/index-e.html) are shortsighted. It is assumed that now cold shutdown has been achieved, TEPCO will announce mid-term to long-term plans and steps for their execution.

IV. DISPOSAL AND CLASSIFICATION OF DEBRIS

NOTE: Some information in Sec. IV comes from the following source:

H. Umeki, "Radioactive Waste Management in Japan—An Overview," presented at IAEA Technical Mtg. Establishment of a Radioactive Waste Management Organization, Paris, France, June 7–9, 2010.

IV.A. Challenges

As discussed in the ANS Committee report, the Fukushima Daiichi accident produced gaseous, liquid, and solid wastes that need to be managed and cleaned up. On-site there was tremendous damage caused by the tsunami surge and the hydrogen explosions, resulting in large amounts of radioactively contaminated debris (with ^{137}Cs being the principal contaminant). Debris removal and cleanup are necessary to provide access to the reactors and support facilities. In addition, removal of the debris allows for these areas to be stabilized so that they will not be a source of further migration of contamination. Radioactive debris is also being generated as damaged reactor building structures are removed to allow access for the future removal of spent fuel and core materials. The contaminated debris is being collected using remotely controlled earthmoving equipment and is placed into large metal containers or within a new solid-waste storage structure. In addition to the on-site debris, there are also solid, low-level secondary radioactive wastes being generated from water treatment operations, from ongoing recovery operations (e.g., personal protective equipment, failed equipment, decontamination wastes, deforestation to make space for storage tanks and buildings, etc.), and from environmental cleanup operations (soils, trees, and other vegetation).

Section IV deals specifically with the issue of on-site radioactive debris, though possible solutions to radioactive waste management, including segregation, packaging, treatment, storage, and ultimate disposal, should also consider the other waste streams, their hazards, and acceptable disposal pathways.

IV.B. Current and Future Conditions

Japan's radioactive waste management regulations classify high-level waste (HLW) and LLW in a manner similar to the U.S. system. HLW is vitrified waste that contains fission products separated from spent fuel during reprocessing and that requires disposal in a deep geologic repository. LLW includes waste from power reactors, research facilities, uranium enrichment and fuel fabrication, and incidental wastes from reprocessing facilities and mixed oxide fuel fabrication. Certain high-activity, low-heat LLW also requires disposal in a deep geologic repository, while other types of LLW may require intermediate-depth disposal, near-surface pit disposal, or near-surface trench disposal depending on the source and activity.

In general, NPP wastes are broken down into three distinct classes:

- waste of core structures, etc.—relatively higher-activity waste such as control rods, core internals, etc.
- LLW from operations—relatively lower-activity waste such as liquid waste filters, used equipment, expendables, etc.
- very-low-level radioactive waste (VLLW) such as concrete and metals associated with decommissioning.

From these three classes of NPP LLW, the core structures would require intermediate-depth disposal, the LLW from operations would be disposed of in near-surface pits, and the VLLW would be disposed of in near-surface trenches.

The development of the process for regulating, investigating, selecting, and licensing a deep geologic disposal site is under way, with the expectation that a site would be licensed and constructed to allow operations to commence in 2040. There are three active near-surface LLW disposal pits, two operated by Japan Nuclear Fuel Limited in Rokkasho and one operated by Japan Atomic Energy Agency in Tokai. Waste is usually disposed of in 200-L drums in these LLW facilities. The VLLW near-surface disposal trenches would be located at or near the nuclear facility undergoing decommissioning. NPPs have the ability to store containerized LLW at their facilities for extended time periods. The estimated quantity of waste at Fukushima Daiichi Units 1 through 4 is ~5 million tons and 3 million m^3; of that, 4.8 million tons are nonradioactive concrete. As there will be large amounts of dismantled concrete, the volume should be reduced by recycling within the site. Waste generated by restoration work is combustible material (several million tons per year), debris (10,000 to 20,000 tons), and contaminated soil (3.7 million m^2).

Japan's radioactive waste management program did not envision the type and magnitude of radioactive debris that is being generated at the Fukushima Daiichi nuclear power station as a result of the disaster. Therefore, use of disposal pits at Rokkasho or Tokai would likely be very limited due to capacity constraints and the need to develop unique packaging and acceptance criteria. Currently, site cleanup at Fukushima Daiichi is being accomplished through the use of vehicles including backhoes, bulldozers, and dump trucks, operated remotely via one of two truck-mounted mobile control rooms. As the debris is collected it is placed in large metal containers and stored in a new solid waste building on site. As of October 17, 2011, the building stores approximately 900 four-cubic-meter and eight-cubic-meter boxes. Deforestation is occurring to clear space for storage tanks and buildings. These contaminated trees are being stored north of Units 5 and 6 in log piles and stick-and-branch piles. The ground space for the previously planned Fukushima Daiichi Units 7 and 8 is also being leveled for debris storage. Each waste container is assigned and labeled with a unique container number, which provides data on where the debris is from, the dose rate, and the type of debris.

IV.C. Recommendations

1. Continued on-site storage of containerized debris is a good practice. Routine inspections should be conducted to ensure that containers are not corroding or damaged. Dispersion of radiation to the environment will be mitigated by storing waste inside buildings as often and as soon as possible. The use of sorbents may be needed if freestanding liquids are present in the containers.

2. The acceptability of using near-surface trenches (located on-site or immediately adjacent to the site) for the disposal of debris should be evaluated, similar to the way demolition debris would be handled under normal circumstances during reactor decommissioning.

3. It should be determined if there are suitable locations for near-surface trenches.

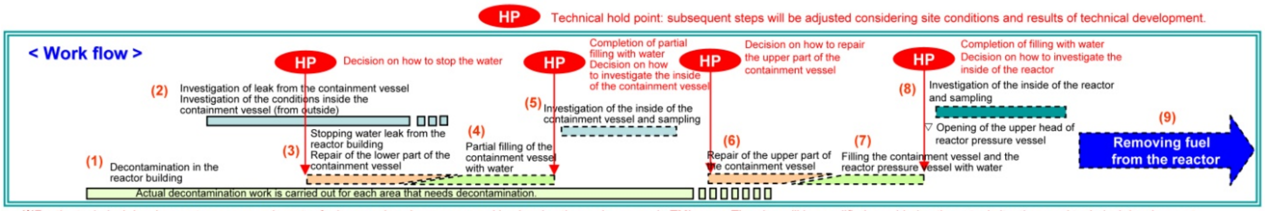
4. Whether or not treatment (such as macroencapsulation, incineration of organic material, etc.) is appropriate should be considered so that near-surface trenches could possibly be used.

5. Development of a multiuse storage and disposal facility (possibly on or near the Fukushima Daiichi site) should be considered. Such a facility would be used for a variety of LLW types, including debris, contaminated environmental media, secondary waste from water treatment activities, and operational LLW. Waste needs to be managed by establishing facilities in accordance with requirements for each stage of the decommissioning activities.

6. Development of a risk-informed end state for the various types of LLW to be dealt with should be considered. This acceptable end state would not only drive the characterization, treatment, and encapsulation options for the various waste streams but would also inform disposal facility design and closure requirements, allowing acceptable performance objectives to be met. Compilation of the nature and quantity of waste, the overall concept for waste management, and the necessary tools and devices as well as a waste management process is recommended. Separation of contaminated parts from noncontaminated parts is needed to reduce volume. As there are large quantities of nonradioactive waste, which will most likely not be allowed to be released, the volume of nonradioactive waste needs to be reduced by recycling within the site boundaries. In the near future, a detailed survey regarding the nature of wastes should be carried out, and waste management needs to be expedited by on-site recycling and development of a facility plan. Integration of domestic technology and the utilization of technologies from overseas will further improve the safety, minimization of waste generation, and efficiency of waste handling.

V. REACTOR BUILDING ENTRY AND ASSESSMENT AND SPENT-FUEL REMOVAL

The high-radiation environment, level of contamination, debris, and damaged structures of the reactor building all challenge the access to the SFPs. There is a belief that some of the fuel in the SFPs is damaged. The strategy to remove debris, access the fuel, and install fuel removal tools to remove and transport such fuel is very difficult and complex (Fig. 1).



※For the technical development purpose, underwater fuel removal work was assumed in planning the work, as was in TMI case. The plan will be modified considering the actual situations and technical development.

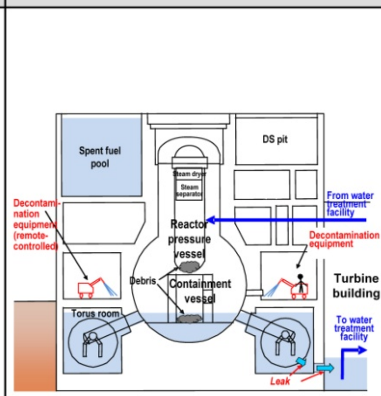
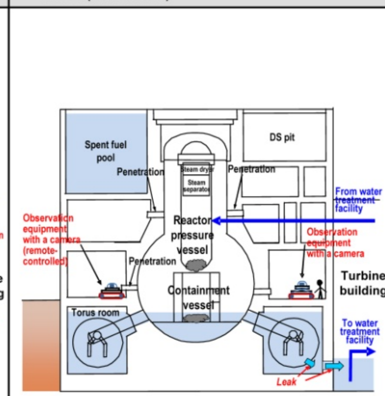
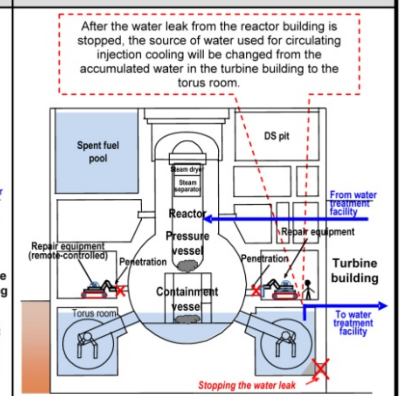
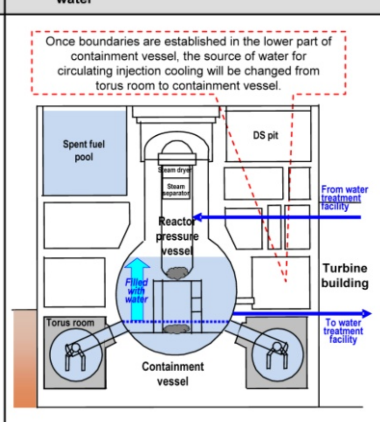
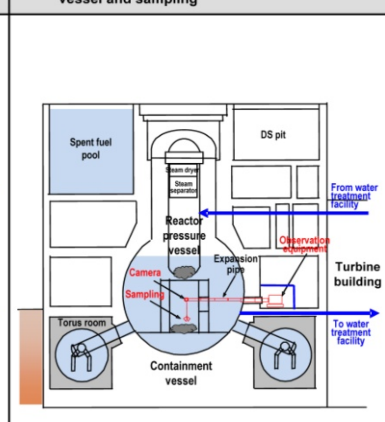
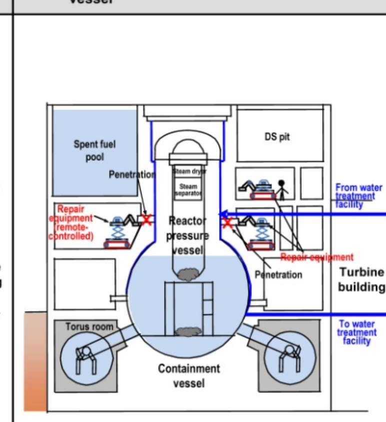
Work	(1) Decontamination in reactor building (Successive decontamination as required for next steps)	(2) Investigation of leak from the containment vessel Investigation of the conditions inside the containment vessel (from outside)	(3) Stopping water leak from the reactor building Repair of the lower part of the containment
Conceptual diagram			
Details	The work area will be decontaminated using high-pressure water, coating, surface chipping, and so forth in order to provide greater access to the containment vessel.	Investigations will be conducted of leak in the containment vessel and the reactor building manually or using remote-controlled radiation dose measuring instruments, cameras, and other devices. The condition of the interior of the containment vessel will be investigated and estimated from outside through γ rays measurements, acoustic investigations, etc.	Since underwater work for removing damaged fuel is preferable in terms of radiation shielding, leaking points of containment vessel will be repaired to stop leakage. For that purpose, priority will be given to repairing the lower parts of containment vessel to facilitate inspection within containment vessel.
Points & issues to be considered in technological development	◆ High dose areas (some hundreds to 1000 mSv) ◆ Limited accessibility due to rubble in buildings • It is necessary to consider remote decontamination methods and other measures for locations with high-level radioactivity.	◆ Objects of investigation are in high dose area, in contaminated water, or in narrow space • Development of methods and equipment to investigate leak • Development of methods and equipment to investigate the condition of the inside of the containment vessel from outside	◆ Stop water leak under high dose and water-flowing conditions in parallel with core cooling by circulating water injection • Development of technology and methods to repair leak in containment vessel and reactor building and stop water leak • Examination and development of alternative measures

Figure 1. Conceptual diagram of plan for removal of reactor fuel with details provided for steps (1), (2), and (3). (Courtesy of TEPCO.)

Work	(4) Partial filling of the containment vessel with water	(5) Investigation of the inside of the containment vessel and sampling	(6) Repair of the upper part of the containment vessel
Conceptual diagram			
Details	The lower part of the containment vessel will partially be filled with water before investigations of the inside of the containment vessel begin.	The inside of the containment vessel will be investigated to identify the distribution of damaged fuel, which is presumed to have leaked out of the reactor pressure vessel, and to carry out sampling and other types of work.	In order to fill the containment vessel with water to its top, leak in the upper part of the containment vessel will be repaired manually or through remote control.
Points & issues to be considered in technological development	◆ Same note as that for (3) •The major premise is to build boundaries in the lower part of the containment vessel (including the plan of filling the torus room with grout materials).	◆ Limited accessibility due to high dose, difficult environment inside containment vessel (accumulated water, dropped damaged fuel, etc.) •Development of methods for remote investigations and sampling in the containment vessel where there is high-level radioactivity.	◆ Same note as that for (2) •Development of technology and methods for repairing leak in the containment vessel and stop the water leak (same as in Process (3))

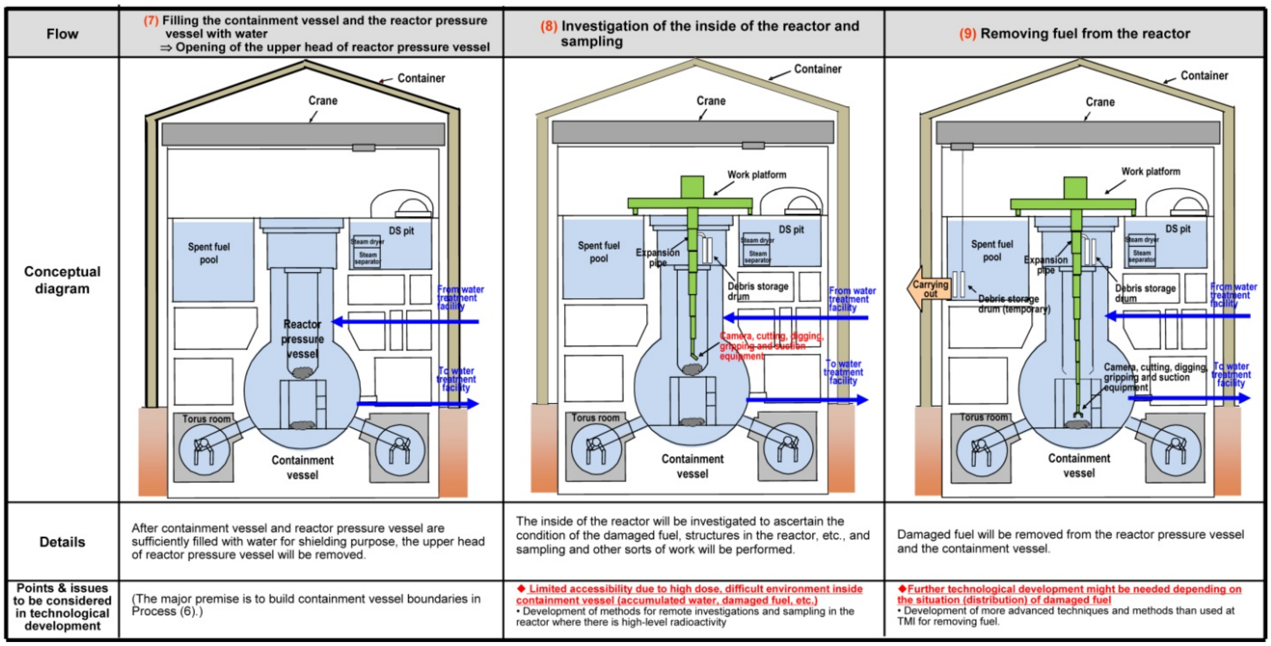


Figure 1 (continued). Conceptual diagram of plan for removal of reactor fuel with details provided for steps (4) through (9). (Courtesy of TEPCO.)

V.A. Challenges

There are a significant number of fuel assemblies stored in the Units 1 through 4 SFPs with Unit 4 having the most and most recently discharged fuel elements. There must be a sense of urgency to reinforce and remove the fuel from these SFPs because of potential future natural phenomena such as earthquakes, tsunamis, typhoons, etc. In addition, structures supporting the SFPs are weakened from the March 11, 2011, earthquake and aftershocks. A total of 81 aftershock earthquakes of magnitude 5.5 or greater occurred between 2:46 p.m. and midnight the night of March 11. Additional challenges include emptying the common SFP and regulations concerning dry-cask storage. The regulatory issues include creation of an interim storage facility and cask design criteria.

Tokyo Electric Power Company believes the Unit 4 SFP and its fuel have not been damaged and will attempt to examine their integrity. If it is shown that they are undamaged, wet transfer to the common SFP can be used. However, a more conservative approach is to assume that the fuel has been damaged and use the appropriate dry-storage casks, which will also be used for Units 1 and 3. The current building cover installed on Unit 1 has to be removed in order to install lifting capability for transportation of casks. The external crane support will be massive and will prohibit the existing cover on Unit 1 and planned covers for other buildings from remaining in place. This demonstrates a current lack of alignment and transition among the short-term, mid-term, and long-term plans.

V.B. Recommendations

1. A cradle-to-grave strategy for removing the spent fuel elements and storing them safely must be developed.

2. The fuel debris and rubble should be placed into robust canisters via the use of a water vacuum and sand filter system.

3. Robotic tools should be designed and examined.

4. Capability to remove and package intact fuel, structurally damaged fuel, fuel rubble, nonfuel structural material, and nonfuel debris/rubble should be developed.

VI. CONTAINMENT ENTRY AND ASSESSMENT AND FUEL REMOVAL

NOTE: Some information in Sec. VI comes from the following source:

"Fuel Removal from Pool and Core," presentation to the Japan Atomic Energy Commission, Tokyo Electric Power Company, August 31, 2011.

The damage to the fuel in the Fukushima Daiichi reactors presents monumental challenges to be overcome in the process of assessing the damage and removing the fuel for ultimate treatment and disposal. TEPCO submitted a preliminary plan for removing fuel from the Fukushima Daiichi reactors and spent-fuel pools to the Japan Atomic Energy Commission on August 31, 2011. The overall outline of the plan for fuel removal from the reactors is described below (also, see Fig. 1):

1. The inside of the reactor building will be decontaminated with robots and remotely operated equipment so that inspection of the containment vessel and leak repairs can be undertaken.

2. The containment vessel will be inspected to determine where water leakage is occurring.

3. The water leaks in the reactor building and the lower portion (torus) of the containment vessel will be repaired. The water level inside the containment vessel will be raised above the level of the damaged fuel to provide additional heat removal and shielding.

4. Remotely controlled equipment will be used to examine and sample the damaged fuel inside the containment vessel.

5. Damage to the upper portion of the containment vessel will be repaired using remotely operated equipment.

6. A containment structure will be installed to enclose the reactor building, and an overhead crane will be installed within the structure. The reactor pressure vessel and containment vessel will be filled with water. The top cover of the reactor pressure vessel will be removed.

7. A wheeled platform will be installed over the containment vessel. Remotely operated equipment including cameras as well as cutting, drilling, and vacuuming equipment will be used inspect and sample the damaged fuel.

8. The damaged fuel will be removed from the reactor pressure vessel and containment vessel. The damaged fuel will be transferred to sealed containers and transported to the outside.

These steps represent only the initial outline of the detailed processes, tasks, and equipment that must be developed to accomplish the examination, assessment, and removal of the damaged fuel from the Fukushima Daiichi containment vessels and reactor vessels. Significant analysis, design, testing, and risk management activities will be required to develop and implement the final plan for fuel removal.

VI.A. Challenges

Many significant challenges must be addressed before the plan described in Sec. VI above can be finalized and implemented. The dose rates within the reactor building and containment vessels will be very high, making it difficult to install and operate the equipment needed to decontaminate the reactor building spaces, inspect the containment vessel for leaks, and remove the damaged fuel. The pathways for operating the equipment must be cleared of debris to allow clear access to perform the necessary decontamination, inspection, and fuel removal operations. The structural capacity of the existing reactor building structures to support fuel removal is questionable. Location of the damaged fuel and cloudiness of the water in the containment and pressure vessels will make it difficult to access, examine, and remove the damaged fuel. Continuous heat removal for the damaged fuel must be maintained during all phases of the process. The containment structure over the reactor building must provide an effective boundary to prevent the escape of radioactive materials during the examination and removal of the damaged fuel.

Identifying and repairing the leaks in the containment vessel so the water level can be raised for fuel inspection and removal will be exceedingly difficult. It is quite likely that there are multiple leaks of many types in the containment vessel that will need to be repaired. Locating the leaks will require very sophisticated methods of remote viewing and other methods such as dye injection. Even then the exact locations of the leaks may be very difficult to pinpoint. These leaks will likely be of a great range of sizes, configurations, materials, and accessibility, so a broad range of access and repair methods will be needed. Leaks in various locations of the containment vessel itself as well as a variety of potential leaks through cable and piping penetrations will be very difficult to reach, and it will be very challenging to apply different repair methods and materials to them.

Some of the most daunting challenges will be the physical processes of installing the overhead crane and the equipment required to examine, sample, and remove the damaged fuel. There are indications that the reactor buildings have been severely damaged or weakened by the accident events, so it is possible that the structural integrity will not be sufficient to support the overhead crane and the associated equipment. This will require the design, fabrication, and installation of an entirely new structure to support the overhead crane.

VI.B. Recommendations

1. The lessons learned from the decontamination, inspection, and fuel removal processes used at TMI-2 and (where applicable) Chernobyl should be carefully examined, as should relevant experience from other industries such as the chemical processing, offshore oil, and aerospace industries.

2. State-of-the-art modeling and simulation tools should be utilized to evaluate the heat removal, criticality, and dose rate parameters for each step of the fuel removal process.

3. The specific methods for equipment installation, containment entry and examination, leak identification and repair, and fuel examination and removal should be developed and tested in a nonradioactive environment to ensure their feasibility and to develop the human expertise required for success.

4. Each step of the fuel examination and removal process should be systematically evaluated to identify the potential pathways and event sequences that could lead to unplanned release of radioactive materials or potential criticality incidents involving the damaged core materials.

5. Multiple levels of physical and administrative barriers should be present and maintained to prevent criticality incidents and the unplanned release of radioactive materials.

6. All equipment should be designed, fabricated, and tested to ensure that it can be operated in the anticipated conditions to achieve the goals of the fuel removal process.

7. Procedures for carrying out the steps of the fuel removal process should be developed with explicit treatment of contingency actions to be taken if unexpected conditions are encountered.

8. Physical and simulator training exercises should be utilized to ensure that all the processes can be carried out without personnel injury, criticality incidents, or radiation release to the environment.