Current status and future planning of Fukushima Daiichi Nuclear Power Station after Great East Japan earthquake

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Fukushima Daiichi Nuclear Power Station (NPS) clean-up and decommissioning activities require a lot of R&D and careful project management due to its severity of damage. Inability of access inside the reactor and turbine buildings due to harsh environment results in large uncertainties which make the project planning difficult. R&D activities will be conducted in parallel with on-site clean-up and maintenance activities. In order to cope with this unprecedented challenge, the government, laboratories, academicians, vendors, manufacturers, and other partners have joined together to support Tokyo Electric Power Company, Inc. (TEPCO). This paper will summarize the current status and mid- and long-term plan for the clean-up and decommissioning of Units 1 to 4 of Fukushima Daiichi NPS as of March, 2012.

Para las actividades de limpieza y clausura de la Central Nuclear (CN) de Fukushima Daiichi, va a ser necesaria mucha I+D, así como una dirección de proyecto concienzuda, debido a la gravedad de los daños. Debido a la imposibilidad de acceder al interior del reactor y de los edificios de turbinas por el ambiente hostil, existen grandes incertidumbres que dificultan la planificación del proyecto. Se realizarán las actividades de I+D en paralelo con las actividades de limpieza y mantenimiento en el emplazamiento. Para hacer frente a este reto sin precedentes, el gobierno, laboratorios, académicos, proveedores, fabricantes y otros agentes se han unido para dar apoyo a Tokyo Electric Power Company, Inc. (TEPCO). En este artículo, se resumirán el estado actual y las previsiones a medio y largo plazo para la limpieza y clausura de las Unidades 1 a 4 de la CN Fukushima Daiichi a partir del mes de marzo de 2012.

CURRENT STATUS OF FUKUSHIMA DAIICHI NUCLEAR POWER STATION

TEPCO and its partners are continuing to put effort into suppressing the discharge of radioactive materials and cooling the reactor at Fukushima Daiichi NPS so as to enable evacuees to return to their homes as quickly as possible and to bring peace to the public. Fukushima Daiichi NPS has achieved the condition equivalent to cold shut down[1] for Units 1 to 3 in December 2011, thereby reaching the aimed target of Step 2 which was set in the restoration work of the accident (all fuel assemblies in the core of Unit 4 were removed at the time of the accident for core shroud replacement; undamaged Units 5 and 6 have achieved cold shut down on March 20, 2011)[1]. A temporary core cooling recirculation system for each unit is working and a large amount of highly radioactive waste water, which is accumulated in the basements of the Reactor Buildings (R/Bs) and Turbine Buildings (T/Bs) of Units 1 to 4, is now being processed and circulated back into each reactor for cooling.

All Spend Fuel Pools (SFPs) in Units 1 to 4 are now cooled with recirculation cooling systems which maintain temperature between 10 and 30 degrees Celsius as of March 2012[2]. There are more than 3000 fuel assemblies in the SFPs in Fukushima Daiichi NPS, and these should be transferred out as early as possible to enhance safety. Because Unit 4 was having core shroud replacement during the accident, it has most number of spent fuels in its SFP with 1535 fuel assemblies. As of March, 2012, no damage to the spent fuel assemblies in the Unit 4 SFP was found based on water sampling and visual check via remote camera[3]. Purification and desalination of SFP water has been implemented at Units 2 and 4 (which seawater was injected during the accident) to prevent corrosion of components in the SFPs. At Unit 3, removing of radioactive rubbles and other materials is in progress prior to desalination of the SFP. Renovation work at Common Spent Fuel Storage (CSFS) for accepting spent fuel assemblies from each SFP is also in progress.

During the first months of the accident, water including high concentration of radioactive materials was leaked into the sea[4]. Silt fences and

[1]Cold shutdown is defined as: (1) Temperature of Reactor Pressure Vessel bottom and containment is lower than 100°C; (2) Radioactive release from the Containment is under control and public radiation exposure by additional release is being significantly held down (not exceeding 1 mSv/year at the site boundary as target)

underground shields were placed in an attempt to mitigate the sea water contamination and to prevent radioactive materials from flowing into the underground water and the sea, while decontaminating the seawater with newly-built seawater purification facilities. Construction work for installing additional water shielding walls on the front of the existing breakwaters in front of Units 1 to 4 is now in progress. As of March, 2012, the maximum concentration of radioactive materials in the seawater within the Fukushima Daiichi NPS port (inside the silt fence) was 200Bq/L for Cs-134 and 270Bq/L for Cs-137[5][2].

Existing Cesium treatment facilities cannot remove most of the other radioactive nuclides. In order to further reduce the radiation level of contaminated water, new decontaminated water processing facilities are now implemented on trial basis to remove multi-radioactive nuclides[6]. As a result, significant reduction in radioactive isotopes to non-detectable level has been observed.

Hydrogen explosions in R/Bs of Units 1, 3 and 4 have caused radioactive debris to be scattered throughout the site. For the management of these radioactive waste and dose reduction, dispersion inhibitor has been sprayed throughout the site. Removal and storage of scattered debris are on-going to allow further recovery work around the site. A R/B cover for the Unit 1 has been completed in October, 2011, and the covers for Units 3 and 4 are also scheduled to be complete in March 2013 and mid-2012, respectively. In the mean time, removal of debris from the upper damaged part of the R/Bs of Units 3 and 4 is in process.

To suppress the emission of gaseous radioactive material from the containments and to monitor the hydrogen concentration and sub-criticality (Xe-135, etc.), containment gas control systems are implemented at Units 1(December 2011), 2(October 2011) and 3(March 2012)[7][8][9]. The emission rates of radioactive materials from Units 1 to 3 are conservatively estimated to be about 70 million Bq/h (Cs-134 and 137) as of January 2012. This is approximately 11 millionth of the estimated maximum emission rate on March 15, 2011[10].

In order to determine the future schedules and to develop necessary tools for decommissioning, it is critical to find the situation inside the containments and pressure vessels such as temperature, radiation level, humidity, available spacing, and etc. Specifications, limitations and criterion can then be developed based on these conditions. As a first step, initial investigation on the inside of Unit 2 containment using a borescope including visual camera and thermocouple through a cable penetration has been done in January, 2012 to acquire information such as visual image, temperature and accumulated water level inside the containment[11]. Investigation on Unit 3 will follow as working condition inside the reactor building improves in the future. These investigation results are critical in planning and developing future cleaning and decommissioning work and also contribute valuable information to the core status analysis.

Storage areas of ever increasing secondary waste from the processing of contaminated water, debris or any other recovery activities are continuing to grow in its number and increasing in their storage capacities to accept them. The rate of waste generation will continue to be controlled appropriately while further improving the methods to suppress the radiation dose at the site boundary.

Reported radiation doses of workers who had started working at the Fukushima Daiichi NPS from March to December, 2011 showed that 167 workers received more than 100mSv (135 workers with 100-150mSv; 23 workers with 150-200mSv; 3 workers with 200-250mSv; 6 workers with more than 250mSv). Exposure doses of 6 workers who received more than 250mSv are distributed from 309 to 678mSv[12][3].

Unit 2 had an incident in February, 2012 that one of the thermometers in the lower part of the reactor indicated temperature rise. Investigation has concluded that the increase was due to the thermometer malfunction and the lower part of the reactor was actually cooled adequately; all other thermometers in the reactor and the containment indicated the temperature drop as water injection was increased, and higher resistance value than normal was measured when electric circuit was checked. It was also confirmed that Xenon concentration indicated no criticality (below non-detection level).

MID- AND LONG-TERM PLAN AT FUKUSHIMA DAIICHI NUCLEAR POWER STATION

On December 21, 2011, Japanese Government-TEPCO Council on Mid- and Long-Term Response for Decommissioning adopted the roadmap towards the decommissioning of Fukushima Daiichi Units 1 to 4[13]. Facing many unprecedented challenges, the framework for effective on-site recovery projects and R&D work were established by TEPCO to ensure steady implementation of the mid- and long-term roadmap. The roadmap presents all major on-site and R&D work schedules until the completion of dismantling Units 1 to 4. The roadmap established specific targets in the next three years which are reviewed and updated on a yearly basis. Significant hold points to evaluate and judge the appropriateness of the work schedule and input resource are set beyond three years.

For on-site projects, TEPCO is currently working with approx. 400 partner companies. The mid- and long-term roadmap towards decommissioning is largely divided into the following three phases towards 40 years decommissioning period (Figure 1). Each phase faces many technical challenges as these will be worked on by each assigned group with assistance from the world. The following activities will be focused at on-site during next phases.

On-Site Activities

Reactor Cooling / Accumulated Water Processing

In order to stably maintain the condition that is equivalent to cold shutdown state, newly built cooling water injection system will be maintained carefully to work until the completion of the fuel debris removal (removal is estimated to complete in 20 to 25 years after Step 2). Improvements to the cooling system will be made continuously by assessing the reliability and implementing the necessary improvements of the cooling system. In order to achieve more stable cooling, the water recirculation loops will be simplified in a step-by-step manner. By the end of Phase 2, all accumulated radioactive water in the buildings for all units should be processed continuously with the installation of water shielding walls between T/Bs and R/Bs which will improve the working environment and ease the access inside the buildings. In addition, all leakage points in the lower part of the containments should be

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[2] The legal density limit for emission from supervised areas: 0.06Bq/cm^3 (Cesium 134), 0.09Bq/cm^3 (Cesium137).

[3] The radiation exposure dose limit for emergency purposes was increased to 250mSv as an exceptional measure on March 14, 2011. Then this was lowered back to the original dose limit of 100mSv after reaching the goal of Step 2 on December 2011.

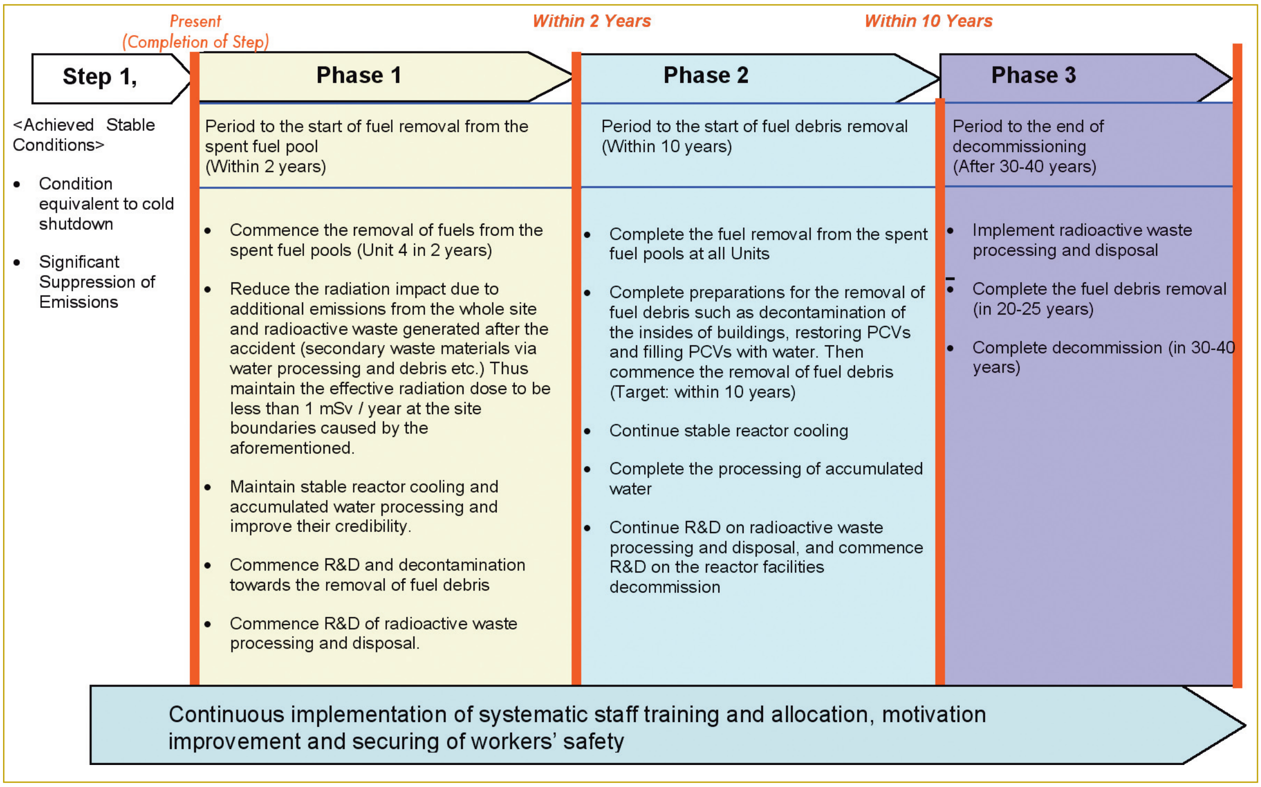

Figure 1: Mid- and Long-Term Road Map.

identified and repaired but this is one of the biggest challenges as described in later section.

Reducing Radioactive Dosage and Mitigation of Sea Water Contamination

Dosage below 1 mSV/year at the site boundaries is targeted by April 2013. Reduction of radiation dose from stored debris and secondary waste produced from the processing of water will be supported by establishing shielding. In order to reduce radiation exposure to the public and workers while improving working environment, step-by-step decontamination measures will be implemented at the site starting from the offices and working areas such as the Seismic Isolated Building in conjunction with efforts to reduce radiation dosage outside the site.

Bentonite-based covering on seabed soil in front of the intake canal is done in March, 2012 in order to prevent the diffusion of radioactive materials in the soil (Figure 2). While monitoring underground and seawater, continuous operation of the circulating seawater purification facilities should reduce radioactive materials inside the site port. Should underground water be contaminated, water shielding walls will be installed in order to prevent underground water flowing into the ocean (Figure 2).

Research and Development Activities

For R&D, fundamental principles for implementing R&D activities are: (1) address on-site technological needs; (2) government involvement and support; and (3) open and flexible framework for implementation with support from international engineering and scientific communities. As of March, 2012, 18 projects are identified in the following areas to address technical needs for the decommissioning work (Figure 3):

- Retrieval of fuel assemblies from SFPs;
- Treatment and disposal of radioactive waste;

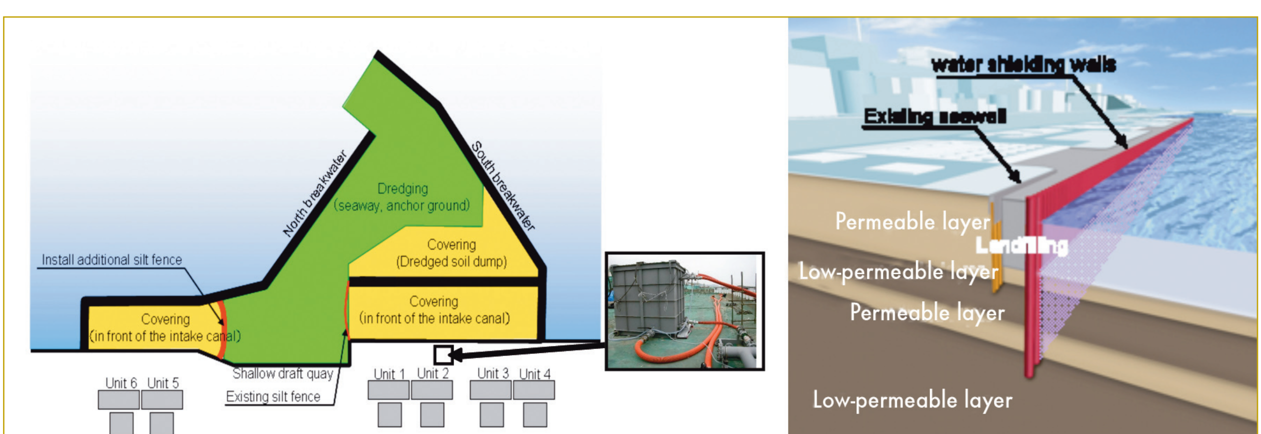

Figure 2: Seabed Soil Covering (left) and Harbor's Water Shielding (right).

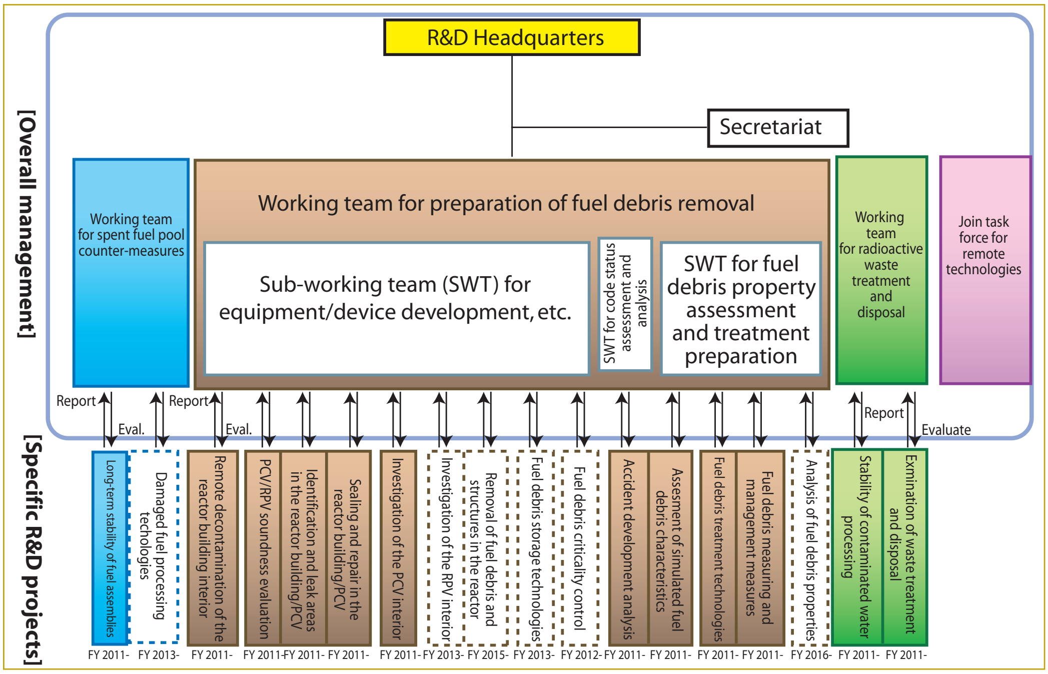

Figure 3: Organizational Structure.

- Removal of fuel debris from reactors;
  - Development of remote controlled equipment and device.
  - Core status analysis.
  - Fuel debris characterization and processing.

Out of above 18 projects, 12 projects have already commenced under the auspices of the Japanese government in collaboration with academicians, national laboratories, vendors, manufacturers and other partners.

R&D Activities for Retrieval of Fuel Assemblies from SFPs

Removal of fuel assemblies from SFPs of Units 1 to 4 is planned with newly built covers over the reactor buildings which are integrated with equipment for fuel handling and removal (Figure 4). Unit 4 fuel assembly removal is scheduled to begin first within 2 years of Step 2 (during 2013). Unit 3 is planned approximately 3 years after Step 2 (end of 2014). For Units 1 and 2, the spent fuel removal plan will be developed based on the knowledge gained from Units 3 & 4. All spent fuel assemblies from SFPs will be removed during Phase 2. Reprocessing and storing methods in the long-term for removed spent fuel assemblies will also be considered during Phase 1.

Long-term integrity of spent fuel assemblies that are immersed in water with salt, hydrazine and other substance will be studied also to assess the corrosion characteristic and storage performance of spent fuel assemblies. This study will be performed at different laboratories where environment condition of Fukushima Daiichi SFPs is simulated.

R&D Activities for Treatment and Disposal of Radioactive Waste

In addition, R&D activities have also started for treatment and disposal of large amount of radioactive debris, for cases of debris from the accident, dismantling of Units 1 to 4, and secondary waste from the processing of contaminated water. Unlike ordinary waste during normal operation, the waste from Fukushima Daiichi NPS can include FP nuclides such as Cs-134, Cs-137 and Sr-90. In addition, the long-term storage effect of sea water salt and other chemical which is included in some of the waste should be examined before deciding which containers or barriers to be selected. Thus, effective and practical method for determining the characteristic of waste such as radioactivity and chemical composition should be developed for determining their storage, treatment and/or disposal method. Based on the result of R&D in this area, safety regulations and technical standards should be developed accordingly.

Due to a large amount of waste to be analyzed in future, an addition of large analysis center including hot laboratories is planned. Training and qualification of sample analysts will be required for this purpose.

R&D Activities for Removal of Fuel Debris from Reactors

The period from the Step 2 to fuel debris removal for Units 1 to 3 is estimated to require 20 to 25 years with molten fuel possibly being leaked from the containments. In comparison, it took 11 years for Three Mile Island Unit 2 with its fuel remained in its reactor. One of the biggest challenge during the removal of fuel debris is to fill containments with water for maintaining radiation shielding and continuous cooling of the fuel. For the containment filling, determination of the methodology to find all the damage (leakage) of the containments and to repair this damage with remote robots which can withstand harsh environmental condition of high radiation, temperature, humidity, limited space and in water environment is critical. Thus, the design, manufacture and testing of remote controlled and other equipment for decontamination, repair, survey/monitoring inside the containments are currently one of the most focused R&D activities in the area of fuel debris removal.

Technology for remote decontamination inside the R/Bs and T/Bs is also prerequisite, and it is currently under preliminary investigation. Feasibility studies on high-pressure washing, coating, scraping and other methods are currently investigated within the scope of national R&D program. Current dose in some of the R/Bs can be as high as 5 Sv/h[12] and many physical obstacles and rubbles in tight space of BWR-4 containment make decontamination work very difficult. Development including field survey and test for decontaminating equipment and the establishment of robot decontamination technology is targeted within 2 years after Step 2.

For the core status analysis, TEPCO has already carried out analysis and evaluation of reactor situation of Units 1 to 3 using a severe accident analysis code MAAP based on acquired operating records and parameters (many assumptions are made due to lack of actual data)[13]. The results were reported to the regulatory body of Nuclear and Industrial Safety Agency (NISA) in May and December, 2011, and it was crosschecked by the NISA with MELCOR to confirm the adequacy of the analysis and evaluation. However, more investigation was necessary for the analysis results, and further clarification of the observed plant data from on-site operators should be done in order to resolve some discrepancies between the analysis results and the measured plant data. For instance, the latest analysis results still show that the Units 2 and 3 Reactor Pressure Ves-

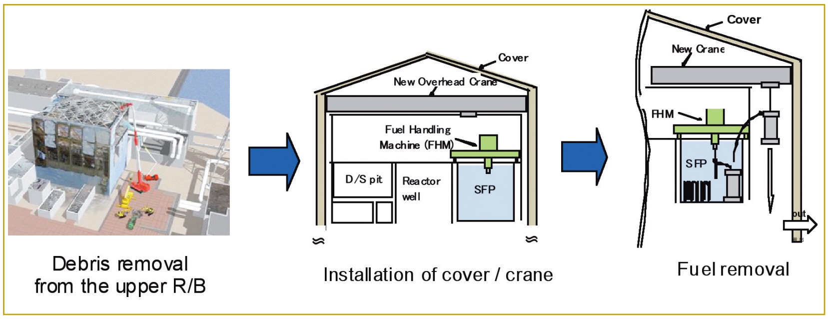

Figure 4: Fuel Removal Process.

sels maintain its containment boundaries, which is not the case based on current actual situation. Further investigation on the analysis criteria and improvement in physical modeling of the phenomenon in the analysis code will be done to lower the uncertainty of the location of fuel debris inside the reactors and containments. Lower uncertainty on the location of the melted fuel will make the planning of future clean-up and decommissioning work safer, more efficient and cost effective.

Other R&D activities which commenced in the area of fuel debris removal include: long-term assessment of fuel assemblies from SFPs; removal, storage, processing and disposal of fuel debris in a safe and efficient manner; establishing methodology for ensuring sub-criticality during defueling; nuclear material accountancy method; and integrity assessment for containments, pressure vessels and concrete pedestals within the containment.

Dismantling of Reactors

By the end of Phase 2 (within 10 years after Step 2), R&D activities of remote dismantlement should be complete and methods for dismantling and decontamination or reactors of Units 1 to 4 should be fixed. Also at this point, actual design and manufacture of dismantling equipment/facilities should commence at the site with the full implementation of modified regulatory oversight. Dismantling of reactor facilities for Units 1 to 4 is estimated to take 30 to 40 years after Step 2.

CONCLUSION

Accident clean-up and decommissioning activities for Fukushima units are more complicated than TMI-2 due to severity of damage in the reactors, containments and buildings. Large uncertainties make project planning difficult, and R&D activities must be conducted in parallel with on-site activities. The programs must change flexibly while facing many unexpected difficulties in future. In order to cope with this unprecedented, long-term challenge, the government, laboratories, academicians, vendors, manufacturers, and other partners have joined together. TMI-2 experience and other relevant research results will be studied thoroughly and will be implemented for the Fukushima case as much as possible. All assistance for these activities from the world community would be very much appreciated.

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