Decommissioning of the Fukushima Daiichi Nuclear Power Station

From Plan-A to Plan-B
Now, from Plan-B to Plan-C

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Disclaimer: The views and assumptions expressed in this report represent the views of the author and not necessarily those of the client. Commissioned by Greenpeace Japan and Greenpeace East Asia Seoul office.

About Author

Satoshi Sato is a consulting engineer, formerly a manager of technology and field engineering with General Electric (GE) Nuclear Division.
For eighteen years (until 2002) he conducted over 100 inspections and assessments at Boiling Water Reactors throughout Japan. He was a GE site representative at the Fukushima Daiichi plant. His work included flaw evaluation, repair, and inspection.

Foreword

In December 2011, nine months after the triple reactor meltdown at the Fukushima Daiichi nuclear plant, Tokyo Electric Power Company (TEPCO) announced that decommissioning of the site will be completed within 30-40 years. The people of Japan were told that some time between 2041 and 2051, the site would be returned to 'greenfield.' In the past decade, the complexity and scale of the challenge at the Fukushima Daiichi site have slowly become clearer, but there remains much to understand.
The decommissioning task at the Fukushima Daiichi site is unique in its challenge to society and technology. But still, the official timeframe for TEPCO's Road Map for decommissioning remains that set in 2011.

What is the reality of current official plans, and are there alternatives?

To try and understand better the progress of TEPCO and possible alternatives, Greenpeace Japan and Greenpeace East Asia Seoul office commissioned consulting engineer Satoshi Sato. A consulting engineer, and having worked for General Electric (GE) for 18 years until the year 2002, including at the Fukushima Daiichi plant, we were looking for an expert opinion on some of the main issues. GE was the principal contractor and designer of the Fukushima Daiichi reactors in partnership with Hitachi and Toshiba.

Sato's analysis points to the many problems with the current plans of TEPCO and the Japanese government. He concludes that the Mid-Long Term Roadmap is unachievable in the timeframe proposed and recommends an alternative path, so-called Plan C.

Ten years after the start of the Fukushima Daiichi disaster, the reality of the worst nuclear accident of the 21 st century needs to be acknowledged and for the Japanese government and TEPCO to abandon their delusion of the disaster being resolved within decades.

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Abstract

On the tenth anniversary of the Fukushima Daiichi Nuclear Power Plant accident, the timeframe for completion of decommissioning of the nuclear complex remains the same as it was announced in 2011 – within 30-40 years. Milestones have been indeed achieved at the site during the past decade. However, the analysis in this report concludes that the current schedule is unachievable. The thinking that has dominated planning since 2011 needs to be discarded. Issues to be covered in this report include:

- Spent fuel removal
- Reduction in contaminated groundwater
- Delaying fuel debris removal for 50-100 years
- Creating a dry island with containment
- Long term management of the Fukushima Daiichi site as a nuclear waste facility

The criticism of the thinking of TEPCO and Japanese government agencies, such as the Nuclear Damage Compensation and Decommissioning Facilitation Corporation (NDF), is that their current plan has no prospects of success within the timeframe of several decades.

The start of the so called second period in decommissioning is defined as the start of activities associated with the retrieval of fuel debris. This debris is highly radioactive core fuel accumulated inside the Pedestal underneath the Reactor Pressure Vessel as a result of melt-through in March 2011. The NDF had been hesitant to revise earlier plans that were obviously not feasible. Plan A, the retrieval of debris using "Flooded Top Access", was to access from above the Reactor Pressure Vessel and remove the debris while underwater with a flooded containment. It was finally abandoned in 2018 and replaced with Plan B, "Dry Lateral Access". Fukushima Daiichi Unit 2 was selected as a candidate for the Plan B pilot program involving the removal of samples of nuclear debris. Originally scheduled to start in the second half of FY2019 it had already been delayed until FY2021. However, in December 2020, it was further postponed until FY2022.

The current Plan B may be achievable, the removal of small samples of debris, but will not be effective to retrieve the bulk of the fuel debris remaining inside and under the Reactor Pressure Vessel at the scale required. The result will be that options will continue to narrow. Full scale retrieval remains a distant prospect and there is no plan for even how to take small samples from Unit 1 and Unit 3. Radiation levels remain too high inside the Primary Containment.

The most distinctive change in the landscape of the Fukushima Daiichi Nuclear Power Plant after 10 years is the tank farm consisting of more than 1,000 large tanks. This is the result of continuous water injection to cool the fuel debris, mixed with the groundwater which was supposedly isolated by the frozen wall, increasing the volume of contaminated water. A target goal for the reduced daily amount has been proposed. However, there currently is no effective method to resolve the issue.

In the case of the hazards from the Spent Fuel Pools much remains to be done. Removal of 1,533 fuel assemblies from the Unit 4 Spent Fuel Pool was begun in November 2013 and completed in December 2014. Engineering and technical challenges mean that in removal of spent fuel from Unit 1 and 2 pools is now scheduled for FY2024-2026 and FY2027-2028 respectively. However, activities started in April, 2019 at Unit 3, took nearly 2 years and finally ended on 28 February 2021. Fuel assemblies transferred from the Spent Fuel Pools to the Common Pool will be eventually loaded into dry storage casks.

As with all nuclear contaminated material, nuclear waste, the spent fuel has nowhere to go in Japan and will remain on site indefinitely. If ever the fuel debris is retrieved it also will remain on site. Fukushima Daiichi is already and will remain a nuclear waste storage site for the long term. None of these are credibly addressed in the current roadmap.

A fundamental weakness with the current decommissioning model is that there is no organization which challenges the NDF or provides supportive and critical technical advice for NDF. The Council by Relevant Cabinet Ministers on Decommissioning and Contaminated Water Management (Council) for decommissioning TEPCO's Fukushima Daiichi Nuclear Power Plant consists of Ministers from the Ministry of Economy, Trade and Industry, the Reconstruction Agency, the Ministry of Foreign Affairs, the Ministry of Education, Culture, Sports, Science and Technology, the Ministry of Health, Labor and Welfare, the Ministry of Agriculture, Forestry and Fisheries, the Ministry of Land, Infrastructure and Transport, the Chief Cabinet Secretary, the Governor of Fukushima-Prefecture and the president of Tokyo Electric Power Company Holdings. None of these have technical expertise of the level required and are not prepared or qualified to take a lead role of responsibility.

The Medium-to-Long Term Road Map is a document published officially by the Council and the associated plan to implement the Road Map is the Technical Strategic Plan developed and annually updated by NDF. However, in reality, the Road Map is not a directive document intended to be used as an instruction to NDF, nor an upper-level management document with an overview of the technical strategic plan. It is a summary of the technical strategic plan. This means that there is no suitably qualified organization with oversight of the NDF and that there is essentially no or little intervention from outside in reviewing or decision-making of its technical strategies.

A Road Map should show a clear path to reach the end goal. Such an approach would present credible technical strategies for the management of the fuel debris and the other challenges on the site. However, NDF has not confidently demonstrated that it is on the right track and moving towards the end goal.

This report concludes that with a radical rethink there is a feasible option for the Fukushima Daiichi site. After Plan B is rejected comes Plan C. It will involve securing the site from further groundwater migration by the creation of a "Dry Island" concept. Secure multiple building structures will be required for the long term, including new containment over the existing Reactor Buildings. The first major step is to reconsider current plans for fuel debris retrieval in the short term. Reducing the radiological hazard to workers by delay and the parallel development of advanced robotic technology to be deployed perhaps in 50 to 100 years or however long it takes.

Abandoning the current unachievable goal of decommissioning within the coming few decades would be not just an admission of failure – but that was always inevitable. It would be a major step forward where finally the government and TEPCO own the consequences of their actions and take responsibility. It is not a question of whether there is another alternative to the one proposed – there must be an alternative to the current flawed plan. The Plan C unlike the preceding Plans A and B acknowledge the complex reality of the Fukushima Daiichi Nuclear Power Plant site. Time for a change.

Table of contents

Glossary

BWR - Boiling Water Reactor is the type of reactor at Fukushima Daiichi. It uses ordinary water (light water) as both its coolant and its moderator. In the BWR, the water in the reactor core is permitted to boil under a pressure of 75 atmospheres, raising the boiling point to 285°C, and the steam generated is used directly to drive a steam turbine. This steam is then condensed and recycled back to the reactor core.

Control Rod Drive - has the function of controlling nuclear reactions by insertion or retraction of control rods which have neutron-absorbing material. By this process it make changes in core reactivity and when necessary allows for the rapid insertion of all control rods to shutdown the reactor.

Corium - is the nuclear fuel inside a reactor pressure vessel once it has meltdown or melted through the vessel. In the case of Fukushima Daiichi it consists of uranium dioxide fuel, its zircaloy cladding, molten concrete.

Control Rods - are rods made with materials capable of absorbing thermal neutrons without fissioning themselves. They are used to control the rate of fission of uranium and plutonium. The control rods are designed to go between the nuclear fuel assemblies in the reactor core.

CRD Housings - The Control Rod Drive housings are fabricated from austenitic stainless steel and inserted through the control rod drive penetrations in the reactor vessel bottom head and welded to the stub tubes. Each housing transmits loads to the bottom head. The lower portion of CRD housings is primary pressure boundaries.

Criticality - an uncontrolled nuclear fission chain reaction. In the case of Fukushima Daiichi, it relates to concerns that the nuclear fuel debris, also called corium, is at risk of undergoing a re-criticality, meaning a resumption of neutron-induced fission in parts of the corium.

Dry Well – is located inside the reactor containment and houses the reactor coolant system of a BWR. The purpose of the dry well (and wet well) is to reduce the pressure if a LOCA or a MSLB occurs. The steam from a leak in these cases enters the dry well and is directed through submerged tubes into the water of the suppression pool (wet well), where it condenses, and the pressure in the dry well is reduced.

Downcomer Pipes – a series of downcomer pipes in a BWR are used to transfer dry well inerted atmosphere, by venting, into the suppression chamber. The inerted atmosphere is intended to prevent an explosive mixture of hydrogen and oxygen following a LOCA.

CRGT – Control Rod Guide Tubes are part of the assembly of components at symmetrical locations below the BWR reactor core which support the weight of the fuel and allows the movement of control rods into the reactor core to achieve reactivity control.

Hot cells – are shielded nuclear radiation containment chambers. The word “hot” refers to radioactivity. They are required to protect individuals from radioactive isotopes by providing a safe containment box in which they can control and manipulate the equipment required.

LOCA – Loss of Coolant Accident is what occurred at the Fukushima Daiichi reactors units 1-3 on 11 March 2011. The cooling water used to remove residual heat from the reactor core fuel stopped circulating after loss of electrical power to the pumps.

Primary Containment Vessel – The General Electric MK1 design containment at Fukushima Daiichi - units 1 – 5 – consist of several major components - the dry well, a torus-shaped wet well beneath it containing the suppression pool. The primary containment vessel is one of the three main barriers limiting the release of fission products from the BWR nuclear fuel into the environment.

MSLB – Main Steam Line Break is a steam line pipe rupture in the main steam piping system, or main steam (MS) line, which will create a decompression wave and a pressure disturbance that moves through the MS line toward the reactor pressure vessel (RPV).

Pedestal – is a large concrete and steel base inside a BWR which supports the reactor pressure vessel. It is constructed as an integral part of the reactor building foundation.

RPV – Reactor Pressure Vessel is the steel reactor vessel body designed to contain the fuel assemblies, reactor coolant, and fittings to support coolant flow and support structures. It is usually cylindrical in shape and subject to enormous pressure and temperature variations.

SCRAM – is an emergency shutdown of a nuclear reactor affected by immediately terminating the fission reaction. It is also the name that is given to the manually operated kill switch that initiates the shutdown. In commercial BWR reactor operations, this type of shutdown is often referred to as a “SCRAM.”

Suppression Pool or Chamber – also known as a wet well is a chamber, which stores a large body of water and therefore it is commonly called as the suppression pool. It consists of a steel pressure vessel with a toroidal shape (sometimes referred to as a torus). The purpose of the dry well (and wet well) is to reduce the pressure if a LOCA occurs. The suppression pool / wet well or torus is used to remove heat released if an event occurs in which large quantities of steam are released from the reactor or the Reactor Recirculation System, used to circulate water through the reactor.

Torus – another term for suppression chamber or wet well.

X-6 Penetration – the opening on the Primary Containment Vessel through which Control Rod Drives packed in the long box on a cart is carried out for maintenance and also used to return the CRDs after maintenance.

1. Overview of Fukushima Daiichi, 10 years after 3.11 and the future

1.1. Green Field Restoration within 40 Years

A major reactor accident occurred on 11 March, 2011 at the Fukushima Daiichi Nuclear Power Plant as a consequence of the Great East Japan Earthquake. The impact of the earthquake and tsunami led to a series of events that led to damage of the structural integrity of the Reactor Pressure Vessel, the Primary Containment and the Reactor Building. Significant radiological releases occurred to the environment. The owner of the nuclear plant at Fukushima Daiichi, Tokyo Electric Power Company (TEPCO), announced their commitment on 21 December 2011 that the site would be returned to “Green Field within 30-40 years”, which would mean that decommissioning and removal of all contaminated materials would be completed by around 2050.

Since December 2011, when TEPCO released its first roadmap for decommissioning, there have been four subsequent revisions to the plans.[1]

This report assesses what are the prospects for attaining this 40-year goal and what alternatives there may be. As an engineer who had worked at the Fukushima Daiichi nuclear plant I concluded at the time, in 2011, that the TEPCO statement was nothing more than a political statement intended to diffuse the anger of accident victims and the general public. There was no specific plan to achieve the decommissioning schedule. I considered it at the time essentially an impossible commitment rather than a difficult one, and irresponsible of TEPCO to make it.

Turning the Fukushima Daiichi site to “Green Field” would require reducing the dose rate to a very low level, for example, less than 0.04mSv/year (or approximately 0.000005mSv/h) when applying an U.S. Environmental Protection Agency (EPA) standard which is commonly adopted for decommissioning commercial nuclear power plants in the United States. Because this level of dose rate is easily hidden by the natural background and beyond the capability to measure by an instrument directly, the equivalent concentration of radioactive nuclides in the potentially contaminated soil must be measured and confirmed to be less than 7.4Bq/kg which is far below the clearance level of 8,000Bq/kg after a nuclear accident or even 100Bq/kg before accident. If any contaminated soil is above 7.4Bq/kg it must be removed from the decommissioning site, the volume of such contaminated soil in case of Fukushima Daiichi would be as much as 10 million cubic meters.

1.2. The First Road Map for decommissioning – 2011 and “Plan A”

From the early stages after the start of the Fukushima Daiichi accident, it was understood that the greatest difficulty in the entire course of decommissioning of the plant is the retrieval of the nuclear fuel debris which melted through and out of the Reactor Pressure Vessels of Unit 1, 2 and 3. TEPCO initially tried to follow the same approach applied successfully for the 1979 Three Mile Island Unit 2 accident. Such an approach consists of the following steps:

* Remove the top head of the Reactor Pressure Vessel;
* Flood the Reactor Pressure Vessel to shield radiation;
* Access the Reactpr Core by using various remote / underwater tools;

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[1] METI, “Mid-and-Long-Term Roadmap archives”, as of March 2021. The original version dated 11 December, 2011 was updated by the subsequent revisions dated 30 July, 2012, 27 June, 2013, 12 June, 2015 and 27 December, 2019. See: https://www.meti.go.jp/english/earthquake/nuclear/decommissioning/archive_mltr.html

* Remove the fuel debris;
* Load the removed fuel debris into the shielded container for shipment.

This approach was expected to work reasonably reliably and safety as long as the Reactor Pressure Vessel remained intact although some extra time would be required to remove the damaged Moisture Separator and Steam Dryer which are located above the Core. This orthodox approach to decommissioning is called “Plan A” in this report. However, at the time this author strongly doubted the technical capability and decision-making process of the TEPCO team because they were not able to quickly determine it was not deployable for their Reactors. Although all pieces of detail technical information were not available, it was already sufficiently clear that the Plan A could not be deployed for Unit 1 through Unit 3 of Fukushima Daiichi Nuclear Power Plant because the level of degradation of these Reactors was far more severe than TMI.

Firstly, the bottom of the Reactor Pressure Vessel was punctured with large holes which allowed the molten fuel debris to flow out. Therefore, it is not possible to flood the Reactor Pressure Vessel. And even if it is flooded somehow, the fuel debris to be removed is mostly not inside the Reactor Pressure Vessel. The TEPCO team then decided to modify Plan A and step back to redefine the Primary Containment as the flooding boundary. The plan at that time was still to approach the Reactor Pressure Vessel from above and to access by using remote underwater tools to remove fuel debris.

However, TEPCO should already have known that Plan A was not worth pursuing. At that time, they knew that the Primary Containment was exposed to the harsh conditions of high pressure and temperature during the accident, resulting in damages and degradations in many locations. They knew that the Primary Containment could not hold water safely for an extended period of time. In fact, the injected cooling water leaking from the Reactor Pressure Vessel was not contained within the Primary Containment. It immediately leaked through the Primary Containment as well. This was not a surprise because the Primary Containment is the large steel structure fabricated by welding hundreds of pieces of relatively thin carbon steel plates and coated to protect from the corrosion. In addition to the exposure to high temperature/pressure, complicated loads due to thermal expansion were also created. Coatings were peeled off. The stripped metal surfaces were exposed to the corrosive seawater injected during the accident. Accessibility for inspection and repair is extremely difficult, limited if not completely impossible. Flooding such a container with water, constantly worrying about a potential large-scale rupture due to degradation or as a result of earthquake and spending many years to try to remove the fuel debris, is a concept that will not work.

Nevertheless, the TEPCO team[2] was reluctant to give up such a dangerous, unrealistic and unfeasible Plan A for a long time.

Groundwater, processing and nuclear fuel cooling

Since 2011, TEPCO has continued to pump water into the Reactor Pressure Vessels of units 1-3 in an attempt to cool the heat generating fuel debris. The water injection into the punctured Reactor Pressure Vessel of Unit 1 through Unit 3 has continued until March 2021. One consequence of this has been that the injected water, while removing residual heat from the fuel debris, has also extracted water-soluble radioactive nuclides. These include cesium, strontium and tritium. These have then leaked from the Primary Containment and the Reactor Building, and finally into the basement of the Turbine Building through the underground passages, the exact

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[2] The 2011 TEPCO team that drafted the was made up of representatives from the company, as well as the government’s Agency for Natural Resources and Energy (ANRE) and the Nuclear Industry and Safety Agency (NISA). See, TEPCO, “Mid-and-long-Term Roadmap towards the Decommissioning of Fukushima Daiichi Nuclear Power Units 1-4, TEPCO”, 21 December 2011, https://www.tepco.co.jp/en/press/corp-com/release/betu11_e/images/111221e14.pdf. One of the first references to the timetable for decommissioning was made by the Expert Group for Mid-and-long Term Action at TEPCO Fukushima Daiichi Nuclear Power Station – also known as the Japan Atomic Energy Commission Expert Group, which was established by the Japan Atomic Energy Commission in August 2011. It concluded that “The target is that it will take no more than ten years before removal of fuel debris starts. We estimate that the completion of decommissioning will take at least 30 years”.

mechanism as of March 2021 has yet to be identified but have been seemingly connected two buildings. This water is then mixed with the underground water whose original source is the rainfall over the Abukuma Heights located west from the Fukushima Daiichi which travels along the underground water table to the Fukushima Daiichi site before eventually reaching the Pacific Ocean. It is for this reason, that the water to be pumped out of the overall Reactor site had to be always much more than the water being injected into the Reactor Pressure Vessel. Because the pumped water, especially during the early stages, contained large quantity of oil and salt, these must be removed from the water before it is processed through various treatment systems and to then be stored in the steel tanks.

As discussed above, while the fuel debris needed to be cooled down by water injection, the injected water, containing radioactive nuclides at high concentration, as well as some salt from sea water which had been injected as an immediate action during the early stage of the accident, would continuously leak out into the basement of the turbine building. In the turbine building the water then mixes with groundwater thereby increasing the total volume of water required to be processed. A small proportion of the processed water is then pumped back to the Reactor Pressure Vessels of Unit 1-3 for cooling. The larger volume of water not used for cooling is routed to the storage tanks on the site. This is why after a decade of fuel debris cooling and ground water migration, the large tank farm exists on the Fukushima Daiichi site. The carbon steel tanks with a capacity of 1,000 tons of water is fully filled only in 3 days. Over recent years more than 100 tanks were constructed annually and entered service.

The water treatment system in the early stages consisted of the subsystem utilizing chemical agents to precipitate some radioactive nuclides, the zeolite vessels to absorb most radioactive cesium and the reverse-osmosis (RO) membranes to separate the sea salt. The collected sludge / deposit and the spent zeolite absorbers turned dangerously hot due to the large quantity of radioactivity and required a designated place to safely store. TEPCO found that the purity of the processed water was not sufficient and still contained some radioactive materials at unacceptable concentrations and required a better system.

Structural support including Spent Fuel Pools

Another aspect of the initial plan related to securing the structural integrity of what remained of the Reactor Buildings. The reactor accident directly damaged the Reactor Cores of Unit 1, Unit 2 and Unit 3. However, it was Unit 1, Unit 3 and Unit 4 that the associated hydrogen explosion destroyed the Reactor Buildings. The explosion of Unit 2 Reactor Building did not occur because its blow-out panel was blown out when Unit 1 Reactor Building exploded, venting the hydrogen effectively through the opening and prevented the accumulation above the explosive limit. In contrast, the Reactor Building of Unit 4 whose Reactor Pressure Vessel was empty was exploded and destroyed by the hydrogen supplied in reverse flow through the exhaust ventilation duct from the junction at the common duct to which explosive hydrogen was supplied from the Primary Containment of Unit 3 when it was vented.

The intensity of the hydrogen explosion was powerful enough to destroy the roof and walls of the top floor of the Reactor Building into pieces. The broken pieces each contaminated with radioactive material were projected long distances in all directions. In the case of Unit 3, several large chunks fell and penetrated through the roof of the turbine building. As a result, large openings were left, and they allowed the rainwater to flow into the building. Besides the roof and walls, the floor structure was also damaged in case of Unit 1. In all the Reactor Buildings where hydrogen explosion took place, overhead cranes and fuel handling machines were damaged. They fell into the Spent Fuel Pools together with pieces of explosive debris. In the case of Unit 4, the resultant structural degradation caused by the explosion was considered significant even on the lower floors. A concern was raised that the weight of the Unit 4 Spent Fuel Pool which contained the largest number of spent fuel assemblies may not be safely supported. A decision was made, and actions were implemented quickly to reinforce the structure to prevent the potential collapse of the Spent Fuel Pool. Also, transferring the spent fuel assemblies from Unit 4 was considered a high priority, and planned for urgent implementation.

1.3. Foundation of the International Research Institute for Nuclear Decommissioning - 2013 and "Plan B"

The initial TEPCO roadmap / Plan A lacked any credibility and should have been abandoned at an early stage. Available resources should have been focused on more realistic plans. At that time – late 2011-2012 - there were no consideration to rethink the approach within TEPCO and its broader team. In August 2013, a total of 18 entities - the Japan Atomic Energy Agency (JAEA), all electric power companies (except for Okinawa Electric Power Company) and all nuclear plant suppliers - created a new organization called the International Research Institute for Nuclear Decommissioning (IRID).[3] It was given a specific mission to lead the necessary Research & Development to achieve the decommissioning of the Fukushima Daiichi Nuclear Power Plant.

The IRID made announced that it would accept proposals for development of basic technologies in various areas associated with decommissioning activities for Fukushima Daiichi Nuclear Power Station. In response to this request this author submitted a 210-page report on 23 October, 2013 under the title of "Fukushima Closure Plan".[4] It described a new overall concept to entirely replace the existing TEPCO Plan A, instead of proposing any specific technology to be developed. Listed below are some unique characteristic of this new concept and some key points emphasized in this report.

1. A method to cool the fuel debris, a method to retrieve the fuel debris and a method to control the contaminated water are all interrelated. They should not be treated independently but should be considered in an integrated manner when constructing an overall decommissioning strategy.

2. If the fuel debris can be removed from the top of the Reactor Building and with the Primary Containment entirely flooded, the fuel debris cooling can be achieved at the same time. However, the level of associated safety risks is unacceptably high and the preventive measures to mitigate the risk are difficult to implement. The concept of flooding the Primary Containment should not be pursued.

3. The contaminated water will be continuously generated as long as water is used to cool the fuel debris. To cease the generation of contaminated water, it is one of the essential prerequisites to change the cooling strategy from water cooling to air cooling. And once air-cooling has been selected and implemented, the retrieval of fuel debris must be carried out in dry condition. In addition, the flow of underground water leaking into the building must be blocked.

4. The fuel debris cooling with air is considered readily achievable. The estimated heat being generated will be easily dissipated from the external surface of the Primary Containment. One method to maintain the heat dissipation from the external surface of the Primary Containment is the use of air flow through the gap between the Primary Containment and the Reactor Building. The temperature of any part of the Primary Containment boundary is maintained sufficiently low in this way. Certain pieces of equipment and structures may get hot locally. However, none of them requires water cooling to remain cold. In fact, being locally hot does not mean excessively hot considering the fact that even the reinforced concrete in direct contact with the fuel debris contains a lot of steel rebars in high density and is expected to behave as a thermal conductor instead of thermal insulation. Therefore, the possibility of reaching a high temperature, that potentially challenges the structural integrity of the Reactor or causing degradation is low enough. If necessary, this expectation could be analytically demonstrated.

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[3] IRID, "Greeting in Commemoration of the Founding of the Organization", 8 August 2013, see https://irid.or.jp/_pdf/en/20130808_greeting.pdf

[4] Satoshi Sato, "Fukushima Closure Plan" 23 October 2013.

5. Once the water injection has been terminated, the fuel debris will be dried out gradually. Any residual liquid water and moisture inside the Primary Containment will be removed with a dehumidifier by simply recirculating the atmosphere.

6. Rather than a top-down approach, the fuel debris will be retrieved from the bottom of the Reactor. An upward excavation will be made along the center axis of the Reactor Pressure Vessel. Underground hot cells connected in a series will be installed in advance for this purpose. The hot cell for excavation will be integrated with the boundary of the Primary Containment through the Guide Tube. The hot cell is the standard shielded chamber conventionally used for laboratories and the spent fuel reprocessing facilities domestically and internationally. It is typically equipped with manipulators by which operators can handle equipment or materials inside with the direct visual observation from outside through the thick lead glass wall.

7. The underground chamber is divided into four sections of hot cells. From the first section, an end-effector holding a drill bit of tungsten carbide and a vacuum head attached to the multi-axis robot arm will be extended through the Guide Tube to reach and break the fuel debris into small particles, then these will be vacuumed simultaneously and retrieved. The retrieved particles will be homogeneously blended with a neutron absorber (boron carbide) to prevent the potential of criticality. Samples will be collected to analyze the composition of fissile materials. Inside the second section, the collected particles will be loaded into a capsule of square pipe whose outside cross-section dimension is identical to a typical PWR fuel assembly but only half of its length. Inside the third section, a lid is installed and welded on top of the loaded capsule. It will be then inserted into the shielded transfer cask. Lastly in the fourth section, the shielded transfer cask containing a loaded capsule will be lifted for transportation.

8. A loaded capsule contained in the shielded transfer cask once lifted out of the hot cell will be loaded on to a truck and moved to the building where there is a deep pool filled with water. The pool is deep enough to shield the radiation and allow the work to place the capsule and load it into a canister designed to contain PWR spent fuel assemblies for storage. The canister has 37 cells. Two capsules are loaded vertically in each cell. When the canister is fully loaded with 74 capsules, it will then be lifted by the overhead crane with its shielded transfer cask in the same way as it is handled on the refueling floor in the decommissioning plant. The canister will be moved by a special transporter to the storage site and loaded into the concrete dry cask for storage, again in the same way as it is handled in the decommissioning site. (More detailed descriptions with some illustrations for better visualization are presented in the later section of this report.)

9. To better limit the production of contaminated water, the flow of underground water leaking into the buildings must be isolated. A frozen wall may be a possible choice for that purpose. However, it may not be the best choice for the changeable geo-hydrological conditions for long-term application. As a more reliable alternative, a canal connected to the ocean around the site would better isolate the flow of groundwater from the Abukuma Heights. Once such a canal has been constructed, the entire site of Fukushima Daiichi Nuclear Power Plant will be physically separated as on an island. The surface would then been covered with a non-permeable material with a well-designed drainage system to prevent rainfall from being soaked into the ground, and the level of groundwater will be gradually and steadily dropped to seawater level, leaving the entire nuclear site as a “Dry Island”.

10. While giving up the goal to turn Fukushima Daiichi Nuclear Power Plant into “Greenfield site” may be considered a drawback, there may be more potential benefits by having an isolated “Dry Island”. It becomes possible to construct trenches to store the large volumes of radioactive waste above groundwater level. Constructing the hot cells underground will become less difficult with less groundwater. The canal would serve as better security

boundary. Other benefits are discussed below.

11. The treated contaminated water is supposed to contain only tritium with all other radionuclides removed. In 2013 I proposed that some of this tritiated water can be partly consumed in the making concrete blocks to be used for protective walls along the canal. The option to what to do with the remaining tritium-bearing water remains to be determined. The government's task force in 2020 recommended release into the environment, including the discharge into the Pacific Ocean. This is strongly opposed by the local communities in Fukushima.

12. The residual water in the Reactor Buildings will be pumped out, treated and stored. Once the entire site turns to "Dry Island", the groundwater flow will become inactive. It will no longer enter into the Reactor Buildings to continually generate yet more contaminated water. Among several potential pools in the building, the water inside the Suppression Chamber remained there from the early stage of the accident without dilution or replacement with fresh cooling water. A special care must be exercised because of the high radiation risk when it is pumped out for treatment.

13. All buildings in the site will be decontaminated. Useless buildings will have to be dismantled while buildings suitable for the waste storage will be reused as many as possible after any required refurbishment.

The "Fukushima Closure Plan" submitted by this author and outlined above was not considered suitable by the IRID staff. An opportunity to make a 7.5-minute presentation for them was given 10 months later, but it was finally buried under a stack of paper. The IRID staff at that time was still sticking to Plan A. However, the TEPCO team later scrapped Plan A and began to change the direction toward a new concept which has some similar elements with the proposed "Fukushima Closure Plan". The new concept they developed in the revised roadmap is called "Plan B".

Revision of plans and the creation of the Nuclear Damage Compensation and Decommissioning Facility Corporation - and 'Plan B'

A brief chronology how "Plan B" was developed is discussed below.

A public / private organization, called the Nuclear Damage Liability Facilitation Fund, was founded in September 2011. In August 2014, it was subsequently restructured to include the additional responsibility for the decommissioning and the management of contaminated water, and the name of organization was changed to Nuclear Damage Compensation and Decommissioning Facility Corporation (NDF). Since 2014 it has prepared and annually updated the "Technical Strategic Plan", while the government is responsible for publishing the "Medium-to-Long Term Road Map".

On 30 April 2015, the NDF issued a report under the title of "Tokyo Electric Power Company Fukushima Daiichi Nuclear Power Station Decommissioning Technical Strategic Plan 2015 - In preparation for revising the 2015 medium-to-long term Road Map -". This report listed the following three concepts as the candidate options for fuel debris retrieval methodologies and to be pursued in depth after screening.

(1) Flooded Top Access
(2) Dry Top Access
(3) Dry Lateral Access

Among these conceptual methodologies, the third one is based on the concept where the fuel debris is removed from the side of Primary Containment on the first floor of the Reactor Building. TEPCO underwent an organizational change in 2016 and the new company name "Tokyo Electric Power Company Holdings" was announced. As a result, the title of the report from then on was changed to "Tokyo Electric Power Company Holdings Fukushima Daiichi Nuclear Power Station Decommissioning Technical Strategic Plan 20XX" (The title of this document is hereinafter called "Technical Strategic Plan 20XX"). The Technical Strategic Plan 2016 issued on 13 July, 2016 included the same three conceptual methodologies. It commented that "Dry Lateral Access" is suitable for retrieving the fuel debris located on the bottom of Drywell (both inside and outside the Pedestal wall) but the level of difficulty is considered high to access the fuel debris located inside Reactor Pressure Vessel. The concept described in “Fukushima Closure Plan” could be called “Dry- Bottom Access” to be compared with these three methodologies. The author also considered the feasibility of the lateral access but determined that the accessibility into and the mobility inside the Reactor Pressure Vessel are extremely limited and difficult with this approach no matter how the technology of multi-axis robot arm is advanced and decided to propose the bottom access instead. If the issue associated with accessibility/mobility can be resolved, the author would not have had a strong objection against the lateral access.

The next yearly update of the Technical Strategic Plan was issued on August 31, 2017. The three conceptual methodologies were still found there. It commented that the level of technology required to be developed for remotely repairing water leakage is too high and the associated radiation exposure is too high to allow the flooded top access option. Then, in the Technical Strategic Plan 2018 issued on 2, October 2018, NDF finally excluded the flooded top access (Plan A) option out of three candidate conceptual methodologies and expressed an intention to focus only on the dry methodology with an extra emphasis on “Dry Lateral Access”.

The “Technical Strategic Plan 2019” was issued on 9 September, 2019. It described some specific details about a series of processes such as retrieval, loading into a container, and the transfer and storage of the fuel debris for the small-scaled pilot testing. First, the use of X-6 Penetration was proposed as an access to the Primary Containment for the retrieval. “Enclosure” is connected to X-6 Penetration with an air-tight seal so as to share the same boundary as the Primary Containment. The retrieved fuel debris would be loaded into a container in the Enclosure. Then, the loaded container would be placed on a remotely operated cart. The container is then carried out of the Reactor Building and moved to the designated storage facility. Inside the storage facility, samples for analysis are to be extracted. The container is carried out of the facility. The fuel debris in the container is finally stored in the temporary storage cell.

NDF issued “Technical Strategic Plan 2020” on October 6, 2020. Further details have been developed for the pilot testing. Specifically, Unit 2 was selected as a pilot plant. Development of a Robot Arm for access tool, a steel brush and the vacuum container were selected to remove the fuel debris for the pilot testing and the gripper tool, and the grinder retrieval tool were proposed for the large-scale production.

As described above, the development of fuel debris retrieval as of October 2020 proceeded only to the stage where only a conceptual methodology for the pilot testing moved forward for Unit 2. For Unit 1 and Unit 3 where radiological environments and conditions inside Primary Containment are different from Unit 2, separate discussions must be made along different avenues. And whatever knowledge is gained from the pilot testing, they will not be directly applicable to the full-scale production and will not increase the level of confidence that the fuel debris can be retrieved successfully by the same or modified approach.

The goal of pilot testing will be relatively easily achieved. Once an access through the X-6 Penetration has been established, it will not be difficult to take samples in the form easiest to pick up and in the location nearest / easiest to access. However, the full-scale production is completely different. For example, certain locations such as that immediately underneath X-6 Penetration inside the Primary Containment and certain locations inside the Pedestal wall are hard to reach. And the accessibility even harder is inside the Reactor Pressure Vessel. The space in front of the Reactor Pressure Vessel is filled with many interfering components such CRD Housings, ICM Housings and Stabilizers interconnecting them in a rigid and complex manner. They all must be removed in order to gain an access route into the Reactor Pressure Vessel. And even after access to the Reactor Pressure Vessel has been somehow gained, it is anticipated that the solidified fuel debris is fused together with the interior components in complex geometry. They need to be removed. If a robot arm is to be used for this purpose, it must have several more joints than the one used for the pilot testing to provide a better flexibility. Associated motion control of the robot arm itself and the end effector will be much more complicated. The probability of equipment failure will also increase.

Since the fuel debris fused and solidified over the interior components in the Reactor Pressure Vessel may be very hard, it will be time consuming to remove or grind it to powder. To be reasonably confident that the selected methodology works for the production scale, there must be further demonstrations to be run in a staged manner after the successful completion of the pilot testing. Considering many expected difficulties ahead, the author of this report believes that even though NDF's Plan B is more advantageous than Closure Plan for the pilot testing, the level of engineering development for the production scale is still in the premature stage and will eventually turn to be very disadvantageous.

Decommissioning activities other than fuel debris retrieval

Construction of the land-side impermeable wall, the so called "Ice wall" began in June 2014[5] and commenced operations in March 2016.[6] The decision by TEPCO and the government to construct the frozen ice wall with the aim of reducing the volume of contaminated water continue to insist that it has served its purpose. However, it has not prevented the continued build up of contaminated ground water and it looks extremely difficult to prove that the frozen wall has been cost-effective choice. As it is used for an extended period of time in the future, it is only a matter of time that any one or more of 1,500 freezing tubes will begin to exhibit degradation and fail. The cost and personnel radiation exposure associated with the inspection, maintenance and replacement will also increase.

The failed isolation of groundwater flow has resulted and will continue to result in the leakage into the Reactor Buildings and the day-to-day generation of an ever large volume of contaminated water. Although there is a plan to continue to reduce the volume of water entering the site to 100 tons per day by 2025, this is not a sustainable position and there remains no long-term plan.

Transferring the fuel assemblies out of the Spent Fuel Pool is considered to be one of the activities routinely performed and with successful experience. There is no major challenges as long as the handling equipment originally furnished is available and intact, and as long as there is no interfering material blocking the free access. However, losing the fuel handling machine (FHM) and the overhead crane, coupled with a large quantity of explosion debris fallen into the pool, resulted in a significantly degraded work environment and conditions. On 28 February, 2021, TEPCO has finally completed the transfer of the last batch of 566 fuel assemblies from the Unit 3 Spent Fuel Pool, which they started in April 2019 after a lengthy delay since activities at Unit 4 were completed. The averaged production rate at Unit 3 was less than 1 fuel assembly per day. The start of work to remove spent fuel from Unit 1 and Unit 2 have been significantly delayed from their original schedule. It is not important or necessary to blame NDF for this. However, it is important for them to learn a lesson or refresh the realization that there are always some discrepancies between as-planned and as-found, which results in unpredictable problems and unexpectedly being stuck. Although the work environment and conditions were significantly degraded, the work itself is straightforward and still considered highly sophisticated. Even so, it took as long as 10 years to get only to the midpoint of spent fuel removal from the Reactor Buildings.

With respect to the management of waste generated within the site of Fukushima Daiichi Nuclear Power Station, construction of necessary infrastructures such as storage facilities, incineration facilities, volume reduction facilities have been steadily progressing. However, it should be noted that the primary purpose of these activities is to house radioactive waste, currently temporarily stored on the ground in the yard and directly exposed to the ambient environment,

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[5] TEPCO, "Construction of Water-Blocking Ice Wall Starts at Fukushima", 3 June 2014. See https://www.tepco.co.jp/en/press/corp-com/release/2014/1237060_5892.html

[6] TEPCO, "Freezing started for the Landside Impermeable Wall (Ice Wall)", 31 March 2016. See https://www.tepco.co.jp/en/nu/fukushima-np/handouts/2016/images/handouts_160331_02-e.pdf

inside buildings and that the completion of these infrastructures does not mean all of the wastes generated to date can be eventually stored in the building in an organized manner. On the contrary, large volumes of low-level radioactive waste “below threshold” and general industry waste including concrete debris, scraps of steel rebars, beams and pipes, a lot more than the volume of waste to be housed, will be left on site. Even though NDF calls them “recyclable”, they will continue to stay on site until the specific application of each recyclable item has been determined and they are received by the potential users.

1.4. Implimentations of Plan B

Although not explicitly stated, the following implications can be extracted from the description in the Technical Strategic Plan by the NDF.

Returning the Fukushima Daiichi Site to Greenfield is Unachievable Goal.

The meaning of the statement “Turning to Green Field in 40 Years” might have changed from how people originally interpreted it. The original meaning of “Turning to Green Field” is that it no longer has any restrictions or conditions for the new usage of the released site. That would be a reasonable interpretation of what this meant. However, in reality it has a different meaning. Even if the plan was to be successfully carried out and major buildings have all been dismantled, and the site has been mostly covered with grass to make it look literally green, it will not be used for residence, farming, industrial/commercial activities, schools, public facilities or athletic facilities for playing baseball, or a park. For the released land to be used for these purposes, the standard for the dose rate limit would need to be something in the range of 10μSv/year, a level which is typically adopted in some European countries. However, just considering the current contamination level on the Fukushima Daiichi site, it is not possible to meet that standard.

Is this new? No, this was obvious from the first day when the reactor accident began in March 2011. The reason why this is an unachievable goal is not because 40 years is too short. When considering the half-life of radioactive cesium (Cs-137) being as long as approximately 30.1 years, and the amount of volume of contaminated soil to be removed to achieve 10μSv/year, we should be able to easily understand that the goal of unconditional release will still not be achievable even extended to 80 years, 120 years, or 160 years. Such an unrealistic goal should not have been proposed from the beginning. Efforts by spending resources endlessly toward such a goal should be avoided. This is no way to ameliorate the victims of the accident, instead TEPCO and the government should conduct a dialogue based on the reality.

- Successful Pilot Demonstration of Debris Removal at Unit 2 Does Not Assure Successful Full-Scale Fuel Debris Removal.
  As discussed earlier, there is a large gap between the pilot demonstration and the full-scale removal. The working methodology that NDF selected (Dry Lateral Access) may be possible for the pilot demonstration but may not be feasible for the full-scale production work.

- What’s next after removing all fuel assemblies out of the Spent Fuel Pool?
  Moving all fuel assemblies out of the Spent Fuel Pool has been completed at Unit 4 and mostly at Unit 3 to date. This does not mean 50% of spent fuel management has been achieved, as they were only moved to the Common Spent Fuel Pool. All fuel assemblies must be eventually loaded in the Dry Storage Casks. But it should be noted that even loading in the Dry Storage Casks is not the end. Ultimately, under current plans they must be all moved out of the site of Fukushima Daiichi Nuclear Power Station. When and whether it is done depends on the national Backend Polity which has not been fully developed yet. And until it becomes fully developed, the fuel assemblies in the Dry Storage Casks will either continue to stay in the site or moved to the next interim storage site.

- What's next after retrieval of fuel debris?
  The issue associated with the ultimate disposition of spent fuel assemblies also similarly applies to the disposition of the fuel debris even if it has been successfully retrieved by overcoming all difficulties. It will be either continue to stay in the site or moved to the next interim storage site. It should be noted that there is almost no prospect that the fuel debris will be processed in the Rokkasho-mura chemical reprocessing plant which was specifically developed and applied for the intact spent fuel assemblies. Not least because of the unknown chemical composition of the fuel debris. This means that the fuel debris will probably stay for a long period of time in Fukushima Daiichi. At some point if a site for a geological repository is secured then the facility constructed and gets ready for receiving.
- All solid wastes including those not housed in the storage building must be properly dispositioned.
  The issue associated with the ultimate disposition of spent fuel assemblies and fuel debris as discussed above is generally applicable to the radioactive waste that needs to be housed inside the storage buildings on site in Fukushima Daiichi Nuclear Power Station, as well as other wastes, such as concrete debris and steel scraps, that do not require storage buildings but are left unprotected and exposed to the outdoor environment.

1.5. An Alternative to the Current Roadmap and Strategic Plan – the Need for Plan C

When all potential issues ahead are considered in an extra-long-time scale as discussed previously, it becomes highly questionable if fuel debris retrieval as currently envisaged in the TEPCO Mid- and Long-Term Roadmap and the NDF Strategic Plan, so called Plan B is either the best option. It should be understood that retrieval of the fuel debris is not the final goal. Even after completing fuel debris retrieval based on Plan B, there will be a period where nothing will be possible at the site due to the radioactivity present. Although NDF emphasizes the importance of speed in its Technical Strategic Plan, it is not clear that there is any advantage to hasten finishing the fuel debris removal.

An alternative would be to allocate this time, over the next 100 years and more, to prioritize on physical efforts to secure containment and confinement of the site and building structures and thereby prevent the dispersion of radioactive material from the fuel debris. At the same time developments and advancements of new technologies are researched and developed for their potential application for fuel debris removal. The author of this report as well as "Fukushima Closure Plan" 7 years ago originally thought that leaving the fuel debris composed of dangerous fission products and fissile materials in the failed Reactor Pressure Vessel or Primary Containment was out of question. Even now, my opinion is that early retrieval should not be completely ruled out.

However, once the conclusion has been reached that even with current cutting-edge technology it is still not sufficiently matured to achieve the goal safely, confidently and cost-effectively, the next best approach should include the option that the fuel debris should be left as it is. This requires a drastic change of approach by TEPCO and the NDF. But it should not be considered as a step-back but may be positively considered as an innovative paradigm shift.

Specifically, in this new approach which I refer to as Plan C, the Primary Containment is treated as the primary boundary although its containment capability was degraded by the accident, whereas the outer surface of the Reactor Building is modified to improve its containment capability to be treated as the sound secondary boundary.

Needless to say, Plan C is the interim solution not the permanent solution for the confinement of radioactive material. However, maintaining the structural integrity and the confinement of the Reactor Building for 100 to 150 years is not considered very difficult to achieve.

Now, the important question to be answered is what a significant advantage if any would result from this approach? Beyond the reduction in radioactivity of cesium and strontium isotopes due to radioactive decay, down to nearly one tenth, it is unlikely that maintaining the structural integrity and confinement of the Reactor Building by practicing periodical inspection and maintenance endlessly is considered as an effective method for actinide nuclides whose half-lives are much longer. We should not dream of an invention of technology that somehow neutralizes the radiotoxicity in the future. However, a rapid and significant advancement of robot technology is expected to continue in the future because it is already one of indispensable technologies in many areas such as manufacturing, construction, medical, nursing care and even security.

Mining robots and underwater robots have been being successfully used for more than 10 years and their capabilities are being improved constantly. NASA has been developing a robot designed to excavate the surface of the Moon and Mars. However, higher performance may be required for robots working inside the Fukushima Daiichi Primary Containment. They may require capabilities to climb up and down stairs/ladders, while avoiding various obstacles of structures and equipment.

A humanoid robot named “ATLAS” developed by Boston Dynamics for example, made a debut many years ago. This robot has many joints and 28 degrees of freedom. Its athletic capabilities include not only just walking on two legs but also hand standing, forward-rolling, jumping, back-flipping and others almost like a human gymnast. It can also open/close doors, use electric tools, operate the valve handle to open/close, do pipe-fitting and many other sophisticated tasks. Inclusions of laser/plasma welding/cutting will be as a matter of time. The concept utilizing a robot-arm through a penetration of the Primary Containment to access inside the Pedestal wall seems to be primitive and already very outdated. Probably, within 100 years, engineers will be able to build a team of humanoid robots with variety of skills necessary for the intended work activities. They will be able to walk into and work inside the Pedestal wall and the Reactor Pressure Vessel, then skillfully remove the fuel debris by operating tools. NDF is working hard currently to find a way to remove the fuel debris with a robot arm with limited capability and fewer degrees of freedom will be replaced by something more easily and efficiently done in the near future by a team of humanoid robots without any concern about labor accident or radiation exposure.

With a decision to postpone for a period of decades the removal of fuel debris, NDF should focus instead on the following: debris cooling by air, treatment of residual water remaining in the building, decontamination of buildings, removing all unnecessary combustible components and installing fire protection system, upgrading the structural integrity and confinement of the Primary Containment and the Reactor Building. The current development program for the fuel debris retrieval should be terminated once the pilot demonstration at Unit 2 has been completed if it cannot be shut down sooner.

What about ethical considerations, about deferring the solutions at the Fukushima Daiichi site and passing on to future generations - a problem that the present generation had caused? However, trying to apply prematurely technology at great cost, and covering these costs by issuing government loan bonds which then is passed on to the next generation to pay off sounds less ethical. Better to avoid the costs now, set aside future funds and prepare for future generations to cover the costs, and using advanced future technology.

2. Road Map and Technical Strategies for Decommissioning of Fukushima Daiichi

The decommissioning project at Fukushima Daiichi Nuclear Power Station has been being carried out by Tokyo Electric Power Company Holdings, Inc. under the direction of public / private organization, the Nuclear Damage Compensation and Decommissioning Facility Corporation (NDF). The organization representing the government of Japan who is the funder but does not assume an oversight responsibility for NDF is the Council by Relevant Cabinet Ministers et al. on Decommissioning and Contaminated Water Management (Council). The secretariat of the Council is the Ministry of Economy, Trade and Industry (METI). It publishes and updates as needed "Medium-to-Long Term Road Map for Decommissioning Tokyo Electric Power Company Holdings Fukushima Daiichi Nuclear Power Station", while NDF publishes annually the "Tokyo Electric Power Company Holdings Fukushima Daiichi Nuclear Power Station Decommissioning Technical Strategic Plan".

The latest version of the Medium-to-Long Term Road Map is the 5th revision dated 27 December, 2019.[7] The latest version of the Technical Strategic Plan is the one dated 6 October, 2020. The contents of the former are almost entirely overlapping with the summary version of the latter.

In the Medium-to-Long Term Road Map, the entire schedule of decommissioning is divided into the First Period, Second Period and Third Period. Separately, there was a period for the urgent responses required to control/stabilize the accident situation immediately following the occurrence of accident, before this Road Map was developed. Such a period consisted of Step 1 (the state where the radiation level was steadily decreasing) and Step 2 (the state where the dispersion of radioactive material was placed under control and the radiation level was significantly reduced). Their achievements were officially announced in July 2011 and December 2011, respectively. The First Period is defined as the period from the completion of Step 2 to the start of the spent fuel removal from the first Unit. The completion of the First Period was announced in November 2013 when the activities to remove the first batch of fuel assemblies were started. The Second Period covers the period until the time to start removing the fuel debris for the first Unit. NDF states that this will be accomplished by December 2021 when the pilot demonstration at Unit 2 begins (This target schedule has been delayed by TEPCO's announcement on 24 December, 2020 indicating it would be in FY2022 or later when they expect to get ready).

Beyond this point of time, the rest of all decommissioning activities belongs to the Third Period. The target schedule to complete Third Period is 30 to 40 years from the completion of Step 2. However, since the scope of the Third Period is too vast, this schedule is too vague to track. So, NDF defined Subperiod 3-1 under Third Period to include the following four categories of activities and milestone schedules:

1. Management of Contaminated Water
   - Reduce the daily generation of contaminated water below 100m^3 (by CY2025)
   - Reduce the volume of residual water in the Reactor Building by half of that as of the end of CY2020 (FY2022 to FY2024)
2. Removal of Fuel Assemblies out of Spent Fuel Pool
   - Begin to Remove Fuel Assemblies at Unit 2 (FY2024 to FY2026)
   - Begin to Remove Fuel Assemblies at Unit 1 (FY2027 to FY2028)
   - Complete all Fuel Assemblies of Unit 1 to Unit 6 (CY2031)
3. Fuel Debris Retrieval
   - Begin to Remove Fuel Debris at Unit 2 (CY2021)

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[7] METI, "Mid-and-Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station", 27 December, 2019, The Inter-Ministerial Council for Contaminated Water and Decommissioning Issues. See https://www.meti.go.jp/english/earthquake/nuclear/decommissioning/pdf/20191227_3.pdf

   - As mentioned earlier, this schedule was delayed by TEPCO's announcement on December 24, 2020. TEPCO indicated that the start of this activity would be in FY2022 or later
4. Waste Management
   - Concrete Debris, Steel Scraps and other Wastes temporarily stored on Yard to be Stored in Storage Buildings (FY2028)

The basis for selection of four categories above is explained in NDF's Technical Strategic Plan as follows. First, NDF decided to apply the SED (Safety and Environmental Detriment) developed by the UK-NDA (Nuclear Decommissioning Authority) as a quantitative evaluation methodology to reduce the risk induced by the radioactive material. The SED is calculated by the equation below:

SED = (Potential Impact) x (Importance to Control)

Potential Impact :
An index indicating the seriousness of impact to the human body resulting from the internal exposure due to radioactive material intake.

Importance to Control :
An index indicating the likelihood of occurrence of the event concerned.

Based on the results of SED calculations, the following three major risk sources were selected as high priority:

1. Residual Water in the Building and Fuel Assemblies in the pools (Relatively high risk and high priority ranking).
2. Fuel Debris (Currently unlikely to rapidly become a high risk. Premature disposition could worsen the level of risk).
3. Solid Radioactive Waste such as Sludge from Water Treatment System (Unlikely to become a high risk even in the future. However, a proper disposition must be done during decommissioning).

There are two reasons why the author of this report is not convinced that the government and NDF presented logical explanations about their Medium-to-Long term Road map and milestones. First, they did not provide an end state for the Road Map. In other words, their Road Map does not show a final destination. Second, their Road Map only lists major activities to be done randomly. The Road Map, by definition, should show clearly what specific activities form a critical path from the start to the end in a sequential manner.

A Decommissioning Road Map without End State

The Road Map includes a clear statement about the schedule. It says that the Third Period is to finish "within 30 to 40 years after the completion of Step 2". However, strangely enough, the road in the map does not state where they would eventually arrive. The scenery around the goal is still very foggy and cannot be visualized based on their explanation. Because the Road Map is designed to show the route to complete the decommissioning of Fukushima Daiichi Nuclear Power Station, the expected end state should be the unconditional release of the entire site or at least most area of the site. In other words, there should not be any restriction for the future use of the land. The people in the future in the previous site once it has been released should not be restricted from living, farming etc.

Against this expectation, it is clear that their Medium-to-Long Term Road Map does not get to that end state even after the declared completion of Third Period. A large quantity of spent fuel assemblies loaded in the dry casks, as well as the fuel debris, even if removal campaign has been somehow miraculously completed by then, would be still on in the site. In addition, more than ten large storage buildings for the solid radioactive waste would be also there. Piles of concrete debris and scraps of steel rebars/beams "below threshold" would be left on the ground somewhere on the site.

The general radiation level in the site would not meet the criteria of 10μSv/year set forth by some European countries or 40μSv/year per the US-EPA. Therefore, the land would not be used for recreational or industrial purposes. After all, whether it is released or unreleased, it seems most probable that the site would be simply converted to a disposal facility or storage facility for spent fuel and other radioactive waste. However, the Road Map is silent on this.

This may be because Japan has been intentionally avoiding the controversial discussion with regard to the standard or requirement for the radiation level for the end state of decommissioned nuclear power plant. The report published by the World Nuclear Association (WNA) in February 2019 prepared by its Waste Management & Decommissioning Working Group, “Methodology to Manage Material and Waste from Nuclear Decommissioning”[8], discusses practices and requirements in variety of countries including Belgium, Canada, China, France, Germany, Italy, India, Netherland, Rosia, Spain, UK and USA in Appendix B “National End State Requirements”. Japan is not included in this report. According to this report, not a few countries treats the matter case-by-case, where in Belgium, Italy, Netherland and the UK specify 10μSv/year level of radiation for a Green Field site.

The Nuclear Regulation Authority (NRA) of Japan specified “below 1mSv/year at the site boundary” as an allowable increment to the natural background, contributed from the radiation from debris and contaminated water stored on site of Fukushima Daiichi Nuclear Power Station in its notice dated November 2012, “Actions to be taken in Tokyo Electric Power Company Fukushima Daiichi Nuclear Power Plant upon Designation to the Specific Nuclear Facility” and in other notice dated 26 February, 2014 “Regulatory Requirements to Achieve the Effective Dose Limit at the Site Boundary of Tokyo Electric Power Company”. The NRA should clarify that this limit, 1mSv/year at the site boundary, is a special standard and does not apply for the end state of the decommissioned plant in order to avoid a potential misinterpretation.

Milestone without Critical Path

It is uncommon to set milestones for the start rather than for the completion of a project, as NDF does. It also looks unusual that the listed milestones do not have interrelations or sequences among them. Therefore, how close they are to being achieved to or how far they are still away from the completion goal in the Third Period remains unknown by finishing each individual milestone. It is good for NDF to identify the priorities by applying SED. However, they should also identify the element activities to be completed along the critical path to reach as early as possible the completion goal of Third Period. Each elements activity along the critical path should have the target completion date as a milestone for the decommissioning schedule.

Although NDF just identified four categories of activities without any explanation of their significance and their interrelationship in a critical path, the following subsections will discuss each of them and point out some of their potential disadvantages or difficulties to be realized in comparison with other alternative approaches.

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[8] WNA, “Methodology to Manage Material and Waste from Nuclear Decommissioning Waste Management & Decommissioning Working Group” 2019. See https://www.world-nuclear.org/getmedia/e81d115f-70c2-4c47-b208-242acc799121/methodology-to-manage-material-and-waste-report.pdf.aspx

2.1. Management of Contaminated Water

History of Contaminated Water

An increment in volume of contaminated water during a certain period of time is the difference between the amount of water pumped out from the building and the amount of water recirculated back to the Fukushima Daiichi Reactors for cooling. If the amount of groundwater and rainwater flowing into the building is zero, they must be equal. In reality, however, the amount of groundwater and rainwater flowing into the building greatly exceeds the amount of water recirculated. This makes the amount of contaminated water to be processed constantly increasing.

As a possible countermeasure to mitigate this problem, a concept of the frozen wall was proposed in 2013. TEPCO and Kajima Corporation, one of the oldest and largest construction companies in Japan, worked together to develop a construction plan by November to proceed. It was the original expectation that the completed frozen wall would almost completely isolate the groundwater flow from outside although some civil engineering experts had been suspicious about such an optimism and cautioned that some groundwater would bypass the frozen wall and spring out through the fracture zone. Nevertheless, JPY 34.5 billion (US$ 330 million) was invested to construct the frozen wall. A complete formation of frozen wall was announced in August 2017. A total of 1,500 freezing pipes were inserted into the soil to the depth of 30 meters from the ground surface along the 1.5km long perimeter to surround all buildings of Unit 1 to Unit 4. A chemical solution cooled down to minus 30 deg. C was supplied to the pipes to freeze the moisture in the soil to form the wall underground.

According to TEPCO, the in-leak flow averaged over three months during the first winter following the completion of the frozen wall in 2017 was 110 metric tons (tonnes) per day, compared to 490 tonnes per day during the same season in 2015, a significant reduction as much as 380 tonnes per day. TEPCO recognized that this reduction was not entirely from the benefit of frozen wall. In fact, other efforts such as covering the ground surface with non-permeable material and pumping the groundwater from the upstream wells contributed more. TEPCO concluded that the befit from the frozen wall alone was the reduction of 95 tonnes per day. However, Reuters commented that their recent independent analysis of the data showed 141 tonnes per day in March 2018, whereas the average over 9 months before the frozen wall was put into service was 132 tonnes per day, suggesting that the frozen wall is not functioning effectively to reduce the in-leak flow.

It is a well-known fact that the groundwater flow varies seasonally and yearly significantly as a function of precipitation. It was only 83 tonnes per day (monthly average) in January 2018 – dry season, drastically dropped from 866 tonnes per day (weekly average) during the week of 20 – 26 October, 2017 when there was much precipitation due to a typhoon. Similarly, during the week of 24 – 30 October, 2019, the weekly average of in-leak flow contributed from both groundwater and rainfall was 505 tonnes per day. Since this in-leak flow was combined with the flow of 132 tonnes per day in average pumped from the groundwater drain wells located downstream of the buildings which was also contaminated and would flow to the ocean if not pumped out, the total weekly average flow processed during this week was 637 tonnes per day. The total precipitation during this week was 158mm. In 2020, the in-leak flow from groundwater and rainfall, the water pumped out from the downstream groundwater drain wells, and the total were determined to be 360 tonnes, 7 tonnes and 367 tonnes per day respectively. The total precipitation during this week was 145mm. These are compared to the values of 131 tonnes, 6 tonnes and 137 tonnes per day respectively during the week of 26 November through 2 December. There was no rainy day during this week.

As is obvious from the data above, the in-leak flow of contaminated water into the turbine building still continues even more than 3 years after the announcement of complete formation of the frozen wall. Although NDF set a milestone by stating to “Reduce the amount of daily production of contaminated water below 100m^3 within 2025”, there is no specific corrective action plan for improvement explained in the latest “Technical Strategic Plan 2020” published by NDF on October 6, 2020. There is no technical strategy for this attaining this milestone.

Without effective technical strategies, there is can be no confidence accomplishing the milestone.

The author of this report commented in the “Fukushima Closure Plan”, submitted to the IRID in October 2013, that the frozen wall would not be a good choice to effectively isolate the groundwater flow, and proposed an alternative concept named “Dry Island”. In this concept, a 7km long moat, deeper than the seawater level, is dug around the entire site as illustrated in the sketch below. A brief explanation how this concept works is embedded in the sketch.

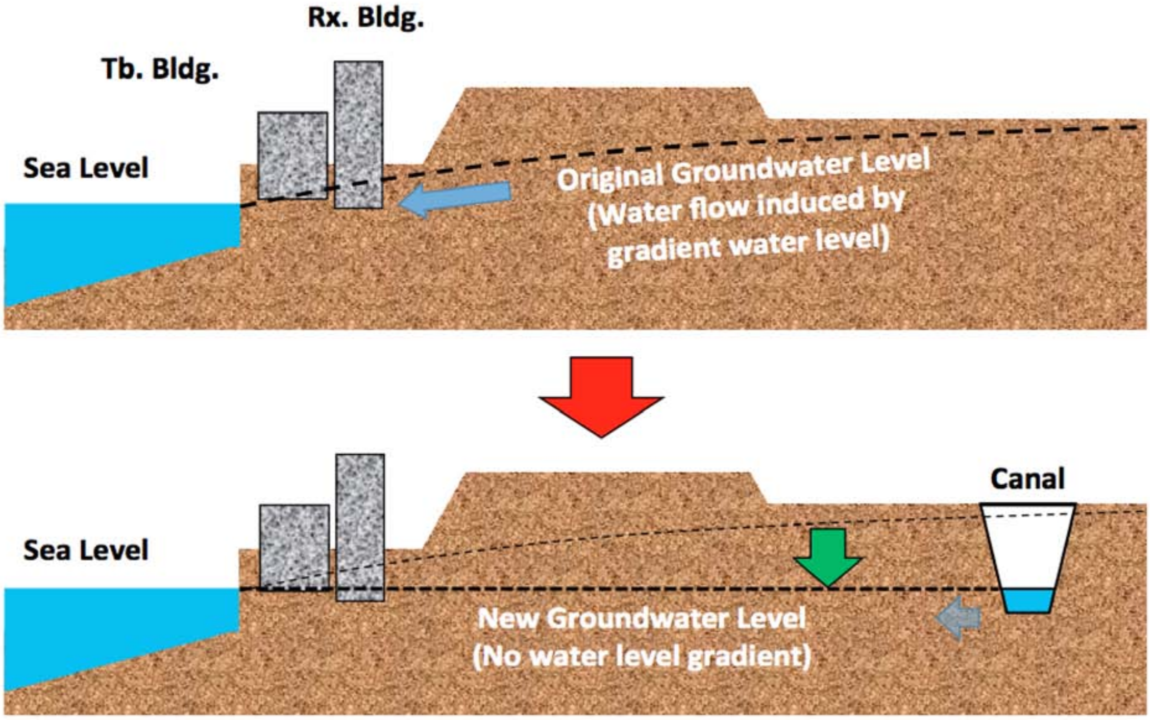


Diagram 1: Dry Island
(Source: Author)

If this concept were implemented and a vast permanent “Dry Island” were developed, not only for the effective management of contaminated water, but also other optional applications become available owing to the lowered groundwater level. For example, large deep trenches could be constructed to store the low-level radioactive waste on site so that there is no need to find an off-site store. The lowered groundwater level also creates the ideal condition for constructing an underground hot cell for retrieving the fuel debris. The moat serves as a robust security boundary just as it did for the castles built in Medieval Ages. In terms of adopting this approach, given how long the Fukushima Daiichi site will have to be managed as a nuclear facility, it is technically not too late to construct this moat. However, NDF will be very reluctant, not least how to justify switching to a new concept after such a large investment into the frozen wall.

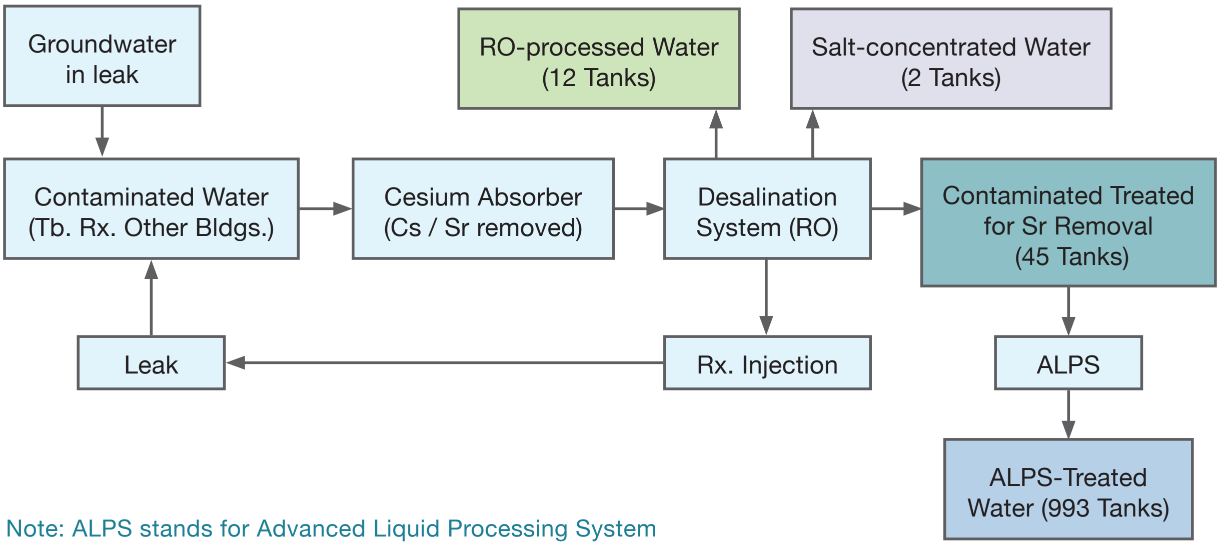
Is there any other effective and reliable way to reduce the generation of contaminated water while leaving the frozen wall left as is? If cooling media is switched from water to air to remove the residual heat, radioactive material in water will no longer be extracted from the fuel debris. The only source of radioactive material carried to the turbine building is the soil in vicinity of leaky buildings. The residual radioactive materials absorbed in the soil will be discharged to the flow of groundwater. The concentration of the waterborne radioactivity will be gradually dropped. How long it would take until the concentration becomes sufficiently low, is hard to predict. However, once it has dropped to that level and stayed there in a stable manner, then pumping water from the turbine building will be finally terminated. Whether this can be achieved before or after CY2025, it is necessary to switch to air cooling as soon as possible.

Is it wise to keep the freezing system running to maintain the frozen wall? As previously mentioned, this system was very expensive to construct. However, just keeping the system running is also very expensive too because it requires the system operation, monitoring, repair and preventive maintenance. An annual running cost was estimated to be more than JPY 1 billion. As long as the system is in serve, it is only a matter of time until certain degradations start to occur. All factors including overall values, long-term reliability and cost for operation, inspection and maintenance should be considered for reevaluation. The moat concept should also be considered.

Treatment of Contaminated Water and Status of Storage

According to "Treated Water Portal Site" administrate by Tokyo Electric Power Company Holdings (https://www.tepco.co.jp/en/decommission/progress/watertreatment/index-e.html), the statuses of the contaminated water treatment and storage as of 19 November, 2020 are as follows:

- Volume of treated water in storage: 1,236,874m^3
- Volume of water treated by ALPS in storage: 1,211,875m^3 (993 tanks)
- Volume of water treated for Sr removal: 24,999m^3 (45 tanks)
- Other processed water: RO-processed (12 tanks), Salt-concentrated (2 tanks)



Note: ALPS stands for Advanced Liquid Processing System

Diagram 2: Status of the contaminated water treatment and storage
(Source: Author)

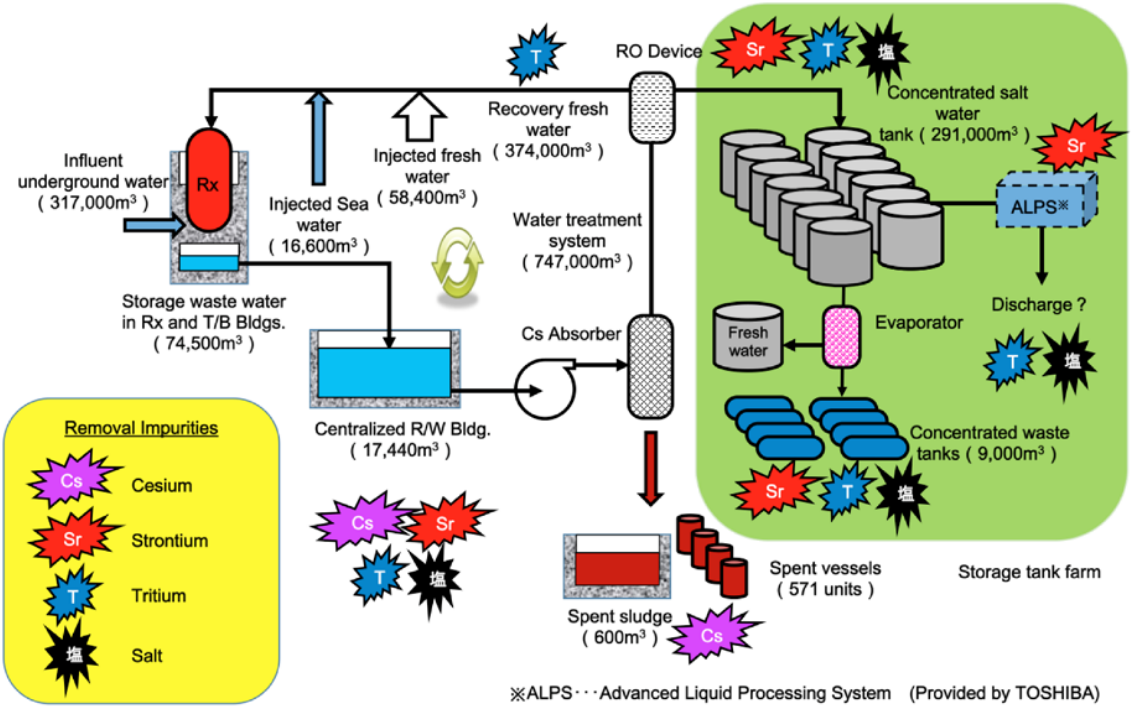
According to TEPCO's original forecast, even though the storage capacity is expanded by constructing more tanks up to approximately 1.37 million m^3 by the end of 2020, it will be all fully filled up by the summer 2022. There are indications that this is changing due to a decrease in accumulation of water and the availability of additional land on the Fukushima Daiichi site.

ALPS-treated water accounts for 98% of all treated water in storage. However, it should be noted that not all ALPS-treated water meets the releasable limit. For the treated water to be releasable, the summation of concentration ratios for all individual nuclides must be below 1. The reason why this releasable limit is not met is not only due to the excessive tritium concentration. Even if the contribution from the tritium is totally excluded, only 27% (295,000m^3) out of all ALPS-processed water (1,122,900m^3) as of 30 September, 2020 was within the limits to release. 1 to 5 times higher than the limit accounted for 34% (374,100m^3), 5 to 10 times higher than the limit – 19% (207,000m^3), 10 to 100 times higher than the limit – 15% (161,700m^3), 100 to 19,909 times higher than the limit – 6% (63,200m^3). Imagine how much clean water is necessary to dilute the 63,200m^3 of contaminated water by the factor of 150. Nearly 100 million m^3. If it is to be diluted by the factor of 1,500, nearly 1 billion m^3 of clean water is required. This suggests that the release by dilution is not a practical solution even if it is legally acceptable.

As for the tritium, its releasable concentration is 60,000Bq/L in Japan. WHO's Guidelines for Drinking-Water Quality (2004) specifies 10,000Bq/L. The measured concentrations of all tanks vary over the range from 131,000 to 2,500,000Bq/L, all exceeding the limit. The releasable concentration limit for the radioactive strontium (Sr-90) is 30Bq/L. However, due to a malfunction of filters of the exiting ALPS units occurred during FY2013, some carbonate deposit slurry leaked to the discharge, resulting in an extraordinarily high concentration value, 433,000Bq/L.

"Tritium Water Task Force" of METI listed five options including "ocean release" in its report published in June 2016. However, no decision has been made since then because of a strong protest from the local fishermen.

When author of this report wrote "Fukushima Closure Plan", this issue was troublesome. At that time, ALPS has not been put into service yet. Contaminated water was processed only by the cesium (Cs) absorber and the RO equipment. The volume of the intermediate processed water stored in "Concentrated Salt-Water Tanks" still containing strontium (Sr), tritium and salt at high concentration reached 291,000m^3 as of 24 September, 2013 (See a sketch below).



※ALPS···Advanced Liquid Processing System (Provided by TOSHIBA)

Diagram 3: Operation Status of Contaminated Water Treatment System as of 09/24/2013
(Source: Author)

The author at that time assumed that only tritium would remain in the processed water because it cannot be removed even after the ALPS has been put into service eventually and proposed a way to consume as much as possible, specifically producing concrete blocks that are necessary for protecting the moat from erosion. Tritium is a unique radioisotope that emits only low-energy and low-penetrating beta ray. Its radiotoxicity can be almost completely blocked by this method. Some relevant literatures were reviewed to confirm that the concrete can be solidified with the salt water at the expected concentration. However, the volume of water to be processed was already too much even at that time. It was concluded that only one quarter of the total amount can be consumed in this way, and the remaining volume must rely on the diluted release.

The problem associated with the contaminated water is not just the final disposition of water stored in tanks on site. The volume of the secondary waste generated from the treatment system such as the chemically produced precipitation deposit and the ALPS absorbent contained in the HICs (High Integrity Containers) has been increasing and now takes a large space for storage. The long-term management of the contaminated water requires transparency and full consultation with the local communities of Fukushima prefecture.

2.2. Retrieval of Spent Fuel Assemblies from Spent Fuel Pool

Spent Fuel Inventories

Immediately prior to the accident, 400 fuel assemblies were in the Fukushima Daiichi reactor Unit 1, while 292 spent fuel assemblies and 100 new fuel assemblies were in the Spent Fuel Pool. Likewise, 548 were in the Fukushima Daiichi Reactor Unit 2 , 587 and 28 were in the Spent Fuel Pool. And 548 were in the Fukushima Daiichi Reactor Unit 3, 514 and 52 were in the Spent Fuel Pool. A major modification project for the reactor internals was in progress at Unit 4. All fuel assemblies had been discharged from the Reactor Pressure Vessel and its Spent Fuel Pool in Unit 4 which contained 1,331 irradiated fuel assemblies and 202 new (non-irradiated) fuel assemblies. As a result of the accident, a total of 1,496 fuel assemblies then inside Reactors of Unit 1 to Unit 3 were affected.

For those spent fuel assemblies and new fuel assemblies not affected by the accident, the retrieval campaigns have been carried out as follows to date. First at Unit 4, the associated campaign for a total of 1,533 assemblies started on 18 November, 2013 and completed by 22 December, 2014. The next campaign was planned for Unit 3 and started on 15 April, 2019. After several troubles and shutdowns were experienced, the last batch of 566 fuel assemblies was removed from the Spent Fuel Pool of Unit 3 on 28 February, 2021.

As for Unit 1 and Unit 2, there is still much time-consuming preparation work to be done. According to the latest Medium-to-Long Term Road Map, the campaign for Unit 2 (total 615 fuel assemblies) is expected to begin around 2024 to 2026 and for Unit 1 (total 392 fuel assemblies) around 2027 to 2028. The previous version of Technical Strategic Plan 2018 dated October 2, 2018 predicted the start at Unit 3 around middle of FY2018, and the starts at Units 1 and 2 around FY2023. This means that the expected starts at Units 1 and 2 were significantly delayed during only the last 2 years.

A decision for decommissioning Units 5 and 6, located within the same Fukushima Daiichi Nuclear Power Station, was made and officially announced later although their Reactors were not directly affected by the accident and remained intact. Since then, all fuel assemblies have been transferred to their Spent Fuel Pools. There are a total of 1,374 spent fuel and new fuel assemblies currently stored in the pool of Unit 5. In Unit 6, 1,456 spent fuel assemblies and 198 new fuel assemblies are in the Spent Fuel Pool and additionally 230 new fuel assemblies are stored in the New Fuel Vault. They are waiting for the completion of the fuel transfer campaign at Unit 1.

Most of the spent fuel and new fuel assemblies transferred from each unit so far are now in the Common Pool within the same site. As a result, total numbers of fuel assemblies in the Common Pool as of 30 September, 2020, including those already there before accident are 6,365 spent fuel assemblies and 76 new fuel assemblies.

Additional 2,033 spent fuel assemblies collected from Unit 1 to Unit 6 are loaded in Dry Casks are also stored on the site. Therefore, excluding 1,496 fuel assemblies originally in the Reactor Pressure Vessels of Unit 1 to Unit 3 and melted during accident, a total of 13,137 spent fuel and new fuel assemblies are either in the Spent Fuel Pool, the New Fuel Vault, the Common Pool or in the Dry Casks.

TEPCO intends eventually to load all spent fuel assemblies in the Dry Casks into the Temporary Storage Facility, a space approximately 21,000m^2, constructed on the site. In the future, an even larger space, approximately 60,000m^2, is also allocated for the temporary storage of fuel debris, once it has been retrieved from Units 1, 2 and 3.

With regard to the final disposition of the large quantity of fuel assemblies at Fukushima Daiichi Nuclear Power Station, TEPCO will possibly face even greater problems after they have completed the retrieval of fuel assemblies from the Spent Fuel Pools which they have identified in the milestones.

Potential Fuel Degradation/Damage occurred during Accident Response

When spent fuel assemblies are transferred from the Spent Fuel Pool in the Reactor Building to the Common Pool, the transportation cask specifically designed for this purpose is used. And a different type of cask (Dry Storage Cask) is used for loading the spent fuel assemblies for the interim storage. There are fundamental differences in the construction and the operation between these two designs. In the case of the Dry Storage Cask, the Canister, a cylindrical shell containing spent fuel assemblies, is capped with a large thick top lid which has small penetrations for draining and venting. After welding the lid to the shell, water is drained and vacuum-dried, then pressurized with helium gas. Small port covers are welded to close the penetrations. This is how the confined boundary of the Canister is established. If there is any penetrating defect on the fuel cladding of any fuel rod of any fuel assembly loaded in the Canister, the gaseous radioactive material (Kr-85) inside the fuel rod is extracted and exhausted to the environment during the operation of vacuum-drying.

During the accident at Unit 3 and Unit 4, the water level of the Spent Fuel Pool significantly dropped from the normal level, and a lot of seawater was either sprayed or injected to make up the lost water. Some salt might have been crystalized on the surface of the fuel cladding. The fuel assemblies have been soaked in the saline water for a long time, potentially undergoing some chemically induced degradation. In addition, they might have been damaged by the concrete debris that fell from above when hydrogen explosion occurred. Nevertheless, when they were loaded into the transportation cask, they were not examined one by one. There was no need to do that. In contrast with the transportation cask, when loading the spent fuel assemblies in the Canister of the Dry Storage Cask, it is important to confirm they are intact or inspect if necessary because the Canister must be vacuum-dried. If there is any small defect on the fuel cladding, the gaseous radioactive material inside the cladding is extracted, and the time to reach the specified vacuum level may take longer. The loading work could be radiologically impacted or extended in these ways.

These potential problems can be avoided by applying a special inspection (vacuum sipping) on each fuel assembly before loading into the Canister. However, it should be noted that this is a time-consuming inspection and the procedure to safely handle such defected fuel assemblies should be separately prepared. The fuel cladding is prone to a metallurgical degradation due to the mild daily thermal cycling over an extended period of time. This is caused by realignment of the orientation of hydride crystals from circumferentially to radially within the zircalloy cladding, losing the mechanical strength against the hoop stress. When this mechanism is combined with the harsh environment, saline water, for a long time, the resultant potential synergistic effects for the long-term storage are unknown. For this reason, it is essential to run the vacuum sipping anyway.

Dry Storage for Long Period or Infinite Period

Although TEPCO could successfully load all 13,000+ fuel assemblies in the Dry Casks eventually and place those loaded casks in the storage facility in the Fukushima Daiichi Nuclear Power Station, how long will they need to stay there in that way? What issues need to be resolved for them to terminate the storage and proceed to the real final disposition? Before these questions are answered, the backend policy must be determined, and the supporting technology must be established. However, there is no nationally accepted consensus yet. Nor is there any proven technology developed yet to support whatever the final disposition would be.

Meanwhile, approximately 200 Dry Storage Casks will stay only in 21,000m2 of space in a concentrated manner. Even if this state is consistent with the concept of SED, the public support would not be expected unless a robust security scheme has been established and maintained. This issue is obviously beyond the discretion of NDF and even jurisdiction of METI. A more thorough intergovernmental review is necessary.

2.3. Retrieval of Fuel Debris

2.3.1 General

According to the Medium-to-Long Term Road Map by the government and NDF's Technical Strategic Plan, there are five basic attributes to be considered while working on the high priority risk reduction activities selected through the SED process. They are:

1. Safety: Radiological Risk Reduction and Enhanced Industrial Safety
2. Reliability: Technologies to be Highly Reliable and Flexible
3. Optimization: Effective Resource Allocation (Manpower, Materials, Budget, Space)
4. Speediness: Schedule Conscious
5. Practicality: To be Strictly Realistic based on Given Environment and Conditions

With these attributions in mind, the unique characteristic to be recognized when developing a specific methodology are listed below. NDF states that they have been also considered when developing a methodology for the fuel debris retrieval.

- Large quantity of radioactive materials, including alpha emitters, which could be a major contributor to the human internal exposure mostly through inhalation is presently unsealed in various uncommon forms throughout the plant.
- Confinement of Reactor Building and Primary Containment is degraded.
- Integrity of the containment boundary of these structure and component is unknown.
- Due to the high radiation levels, accessibility in the plant is limited. Even installing instrumentations to remotely monitor the plant conditions is difficult.
- Rapid actions are necessary because further degradation of containment boundaries is possible.

Access Route for Debris Retrieval

It has been confirmed that most fuel debris had fallen through the failed bottom head of the Reactor Pressure Vessels and accumulated inside the Pedestal wall. Since the very early stage of the accident to date, it has been being cooled by injected water. The Pedestal is the thick cylindrical structure located on the bottom of the Drywell. The Reactor Pressure Vessel, the Pedestal and the Primary Containment share the same axis. The Pedestal is designed to vertically support the weight of the Reactor Pressure Vessel and is constructed with reinforced concrete. Encased in the concrete are thick steel rebars densely arranged. The dimension of inside diameter of Unit 2 and 3 Pedestals is approximately 5.4m, roughly 1 meter larger than Unit 1 Pedestal.

A rotating platform is installed inside the Pedestal for removing and reinstalling the Control Rod Drives (CRDs) for the periodical maintenance, and for disconnecting and reconnecting the signal cables of the in-core neutron detectors for their replacement. The height of platform from the Pedestal floor is approximately 3.2m. An access to inside of Pedestal is essential for retrieving the fuel debris.

While developing a specific methodology to retrieve the fuel debris from the Reactor Pressure Vessel and the Primary Containment for Unit 1 to 3, differences in the distribution of fuel debris, water level inside the Primary Containment, accessibility through X-6 Penetration and the radiation level in the vicinity have been carefully reviewed and considered.

With respect to the distribution of fuel debris within the Core region and in the bottom head inside the Reactor Pressure Vessel, a Cosmic-Ray Muon Radiography was employed to gain information. In spite of its poor resolution, it did provide some useful insight. It required an exposure to the scarce cosmic muons for a long period. At Unit 1, the muon radiography was performed twice. First, from February to May in 2015. Second, from May to September of the same year. At Unit 2, from March to July in 2016. At Unit 3, from May to September in 2017.

“X-6 Penetration” is the opening on the Primary Containment through which CRDs packed in the long box on the cart is carried out for the maintenance and carried in after the maintenance. To facilitate this work, an inclined tunnel with a pair of rails is installed. The other end of the tunnel rests on the rectangular opening on the Pedestal wall at the same elevation as the rotating platform. This penetration is opened only during the periodical inspection and maintenance outage and securely closed during the plant operation. Once the X-6 Penetration is opened, this is the shortest route from the outside Primary Containment directly to the inside Pedestal.

Beside this small rectangular opening at the elevation of rotating platform, there is a door-size opening on the bottom of the Pedestal wall for personnel access. The maintenance personnel can walk into the inside of the Pedestal through this opening from the bottom floor of Drywell.

There are two drain sumps, one for equipment drain, and the other for floor drain, installed on the bottom floor inside the Pedestal.

Survey inside Pedestal

While no remote exploration has been attempted to date to examine the condition of fuel debris accumulated inside the Pedestal for Unit 1, it has been performed three times for Unit 2 (January 2017, January 2018 and February 2019), and once for Unit 3 (July 2017).

From the one performed for Unit 3 in July 2017, some Reactor Internal components such as Upper Tie-Plate of fuel assembly, CRD Index Tube, CRD Guide Tube, Speed Limiter Casting of Control Rod, and various other debris, including some pieces of the grating floor fallen from above, were found mixed within a matrix of sandy, pebbly and a large pile of the fuel debris deposit.

The most detailed remote explorations were performed in Unit 2. From the one performed in January 2018, the Upper Tie-Plate of fuel assembly was found buried in the clayish and pebbly pile of fuel debris deposit which had accumulated on the bottom of the Pedestal. A spring was also found but not identifiable whether it originally belonged to the fuel or the SRNM (Startup Range Neutron Monitor). Video pictures taken during this exploration showed that many components and structures including the cable tray and gratings of the CRD Replacement Cart were broken, deformed and scattered in a chaotic manner. Detailed observation activities were conducted by lowering the Inspection Unit approximately 2m below the platform. Color pictures taken were reasonably clear. During the latest exploration performed in February 2019, some physical tests using a grapple were performed too. The grapple had movable fingers. The team confirmed that they could move the pebbly deposit relatively easily but could not move the larger chunks. Such larger chunks were hard, and no contact mark was engraved on the surface by the grapple fingers. The radiation dose rate was also measured. It ranged from 6.4 to 7.6Gy/h, indicating uniform inside Pedestal. The dose rate reading outside Pedestal was 43Gy/h, higher than inside. Although this sounds contradictory to our expectation and no technical explanation was provided by TEPCO in the document, the author is almost certain that the reason why the dose rate inside the Pedestal is much lower than that outside Pedestal was due to the shielding effect of water for the beta ray. This means that once the fuel debris inside the Pedestal is dried out, the dose rate could increase drastically.

Dry Lateral Access

It was the version published in October 2018, in which NDF's Technical Strategic Plan finally expressed its intention to focus on "Dry Lateral Access" from the first floor of the Reactor Building to retrieve the fuel debris.[9] However, this author of this report sensed an impression at that time that the NDF team was only interested in taking any sample of fuel debris from any location inside Pedestal for the time being, with no intension to apply it for the full-scale retrieval of the fuel debris. For that reason, the author determined that the concept that the NDF team started developing was less realistic than that proposed in "Fukushima Closure Plan" where an access from the bottom was suggested, and that if the team would seriously pursue this concept, they would need a sophisticated robot arm with many joints and degrees of freedom.

Differences among Units 1 to 3 and Candidate Unit for the Pilot Demonstration

Differences in the progression of the accident among Units 1 to 3 are attributed to the different chronologies of actions taken soon after the event of SCRAM shutdown of each Reactor. Specifically, the duration how long the Isolation Condenser (IC) system performed its core cooling function for Unit 1, and the duration how long the Reactor Core Isolation Cooling (RCIC) system survived for Unit 2 and Unit 3 until it lost its equivalent function, were the most critical factors. Unit 1 lost the IC system first, then Unit 3 lost the RCIC system, and lastly Unit 2. Unit 1 being the first explains the reason why it is believed that very little fuel debris remains in the bottom of the Reactor Pressure Vessel, and that most of the fuel debris was drained down to the Pedestal region in fluid form with much of it even flowing out through the opening of the personnel access on the bottom, and spreading over the Drywell floor. Unit 3 with the RCIC system surviving much longer than Unit 1's IC system, is believed to hold some fuel debris in the bottom of the Reactor Pressure Vessel, resulting in the reduction of the amount drained down to the Pedestal region. Therefore, it is assumed that less fuel debris leaked out through the opening of personnel access on the bottom. Unit 2, whose RCIC system survived longer than that of Unit 3, is believed to hold more fuel debris than Unit 3 in the bottom of the Reactor Pressure Vessel, resulting in a further reduction of the amount drained down to the Pedestal region. It is assumed that all drained fuel debris remains inside the Pedestal region.

The water level inside the Primary Containment depends on the degree of damage due to the accident. For Unit 1, the water level has been determined to be approximately 2m from the Drywell floor. Therefore, the X-6 Penetration is not submerged. On the other hand, it is estimated that the Torus is fully flooded. For Unit 3, the water level has been determined to be approximately 6m from the Drywell floor. Therefore, the X-6 Penetration is submerged. It is estimated that the Torus is nearly fully flooded. In the case of Unit 2, the pressure inside the Primary Containment had experienced a significant drop in the course of progression of the Core degradation. This was interpreted as an occurrence of major damage on the pressure boundary of the Primary Containment. The water level has been determined to be only approximately 20cm from the Drywell floor. This level is equivalent to the bottom of Vent Pipes that structurally connect the Drywell to the Torus which is also called the "Suppression Chamber" or "Wetwell". Therefore, the X-6 Penetration is not submerged. It is assumed that the Torus water level had drastically dropped due to the major pressure transient and the bottom of Downcomer Pipes is exposed to the vapor phase, so that the atmosphere inside the Drywell freely communicates to the Torus.

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[9] NDF, "Strategic Plan 2018", 2 October 2018. See http://www.dd.ndf.go.jp/en/strategic-plan/index2018.html

The first floor of the Reactor Building where the major work activities are expected to occur when “Dry Lateral Access” is adopted, is not suitable as the space for the workstation in the case of Unit 1 because the radiological environment is too harsh, specially in the vicinity of X-6 Penetration. The dose rate is as high as 630mSv/h. The dose rate in the same area of Unit 3 is lower but still too high to stay. And there are some hot spots, reading several tens of mSv/h. Even if they are decontaminated or shielded, workers cannot perform activities in a productive manner. After all, only Unit 2 can barely offer the space for the workstation for the small-scale activities. The general area dose rate decayed down below 5mS/h. Normally, this level of dose rate is not considered sufficiently low, but the NDF team might have concluded that this is within an acceptable level for the small-scale pilot demonstration.

Taking all factors above into consideration, Unit 2 was selected for the pilot demonstration for the fuel debris retrieval. Units 1 and 3 are still in the preliminary stage. Additional efforts to gain more information are necessary for these units. Therefore, even if the pilot demonstration at Unit 2 is successful, there is no assurance that the same methodology generically works for the Reactor units. Also, it should be noted that the full-scale production will not be a simple extrapolation of the successful pilot demonstration. There are too many unknown difficulties ahead.

2.3.2 Unit 2

Among the three Fukushima Daiichi Reactor units, Unit 2 has the most favorable conditions for the fuel debris sampling. Some detail discussion is presented in the material “Investigation inside PCV and Status of Preparation for the Fuel Debris Sampling for Unit 2” dated 29 October, 2020 released by Tokyo Electric Power Company Holdings. Some topics of its contents are summarized below along with the author’s comments.

Progress in the Past and Plans for the Future

For Unit 2, in order to determine the feasibility of using the X-6 Penetration, a survey was conducted in January 2017, and the presence of some deposit inside was found. Because it is necessary to understand the characteristics of such deposit, the procedure to remove was investigated. During the 2017 survey, a small hole was cut into the X-6 Penetration, then installed in a guide tube. Using this guide tube, the Inspection Unit was inserted to visually examine the condition of the deposit.

Based on the result of further investigation by physically touching the deposit conducted on 28 October, 2020, it was confirmed that the deposit was soft, easily deformed by touching but not sticky. Cables were also found inside the Penetration. They were flexible and free to move. It was confirmed that they can be lifted by using the Inspection Unit which is equipped with multiple joints, three fingers and illumination. One of the technicians worked to set up the Inspection Unit received 1.5mSv of radiation exposure on this day.

Without preventative measures it is expected that some radioactivity will become airborne during the operation to remove the deposit inside X-6 Penetration. To prevent this, the NDF is planning to install a spray device to the X-53 Penetration which is located near and above the X-6 Penetration for future activities. The X-53 Penetration has an existing 50mm diameter bore hole. However, the outside diameter of the spray device is 100mm, larger than the inside diameter of existing bore hole. NDF plans to enlarge the X-53 Penetration up to 130mm by using a hole saw. A spray device will be installed on the X-53 Penetration after this. A water spray will be activated to establish the spray curtain over the X-6 Penetration. Then, removing the deposit from the X-6 Penetration will be attempted.

Fuel Debris Retrieval

The work to install the spray device on the X-53 Penetration is scheduled for 2021. Following completion of installing the spray device, an Isolation Chamber is to be set up, then proceeding to inspecting inside X-6 Penetration, removing deposit, and finally the fuel debris retrieval.

It should be noted that the fuel debris retrieval in full-scale production remains a long way into the future. The fact that only a preliminary examination on the deposit inside X-6 Penetration cost one technician 1.5mSv of radiation exposure, and that the spray curtain is required to remove such deposit, suggests there could be some major obstacles in the future.

In fact, when the progress and the plan outlined above are compared with those in the Technical Strategic Plan dated 2 October, 2018, some delay and modification are found. In this Technical Strategic Plan, the so-called “Contact Examination”, an investigation by physically touching the deposit inside X-6 Penetration, was planned for the second half of FY2018, and sampling the fuel debris in the Pedestal region was supposedly conducted in the second half of FY2019. Taking more samples with increased quantity were supposedly repeated in FY2020. The modification work to expand the X-6 Penetration to install the debris removal equipment which is manipulated by the arm guided by rails was then supposed to begin from FY2021 toward the full-scale production.

2.3.3 Unit 3

In the case of Unit 3, the X-6 Penetration, an important candidate access route to retrieve the fuel debris, is fully submerged. For this reason, a survey to investigate the condition inside the Pedestal was performed in July 2017 by utilizing the X-53 Penetration which is located immediately above the X-6 Penetration. An underwater Remote Operated Vehicle (ROV) was inserted through this penetration. Analytical efforts were made to graphically construct the as-found 3D geometry inside Pedestal based on the visual information gained by the ROV. However, because not enough time was spent for video taking and pictures were unclear and partial, many items found were unidentifiable, their locations were not determined. The intended graphical 3-D reproduction was unsuccessful.

Since then, no further attempt has been made at Unit 3 to investigate the conditions inside Primary Containment. Therefore, there is currently no plan for retrieving the fuel debris and even no indication as to when such a plan would be developed.

2.3.4 Unit 1

Due to a fatal operational error occurred during the initial response, the progression of accident was fastest at Unit 1 among all three affected Reactor units. As mentioned earlier, most of the fuel debris inside the Reactor Pressure Vessel is assumed to have drained down to the Pedestal region. Only a small amount remains inside. This assumption later turned out to be consistent with the result of the Cosmic-Ray Muon Radiography (Muography) as previously explained. It was also suspected that some of the fuel debris fallen in the Pedestal region flew out through the personnel access opening and spread over the Drywell floor. As if this suspicion was supported by evidence, the dose rate in vicinity of the X-6 Penetration on the first floor of the Reactor Building was extraordinarily high, 630mSv/h. Utilizing this penetration for surveying inside the Primary Containment was judged to be impractical. Instead, the X-2 Penetration (Double Air-Lock Door for Personnel Entry) was selected as a candidate for the access into the Primary Containment.

The X-2 Penetration in Unit 1 locates at 270-degree azimuth. This orientation is greatly away from the azimuth of the X-6 Penetration which is approximately 160-degree. This means that even if an entry through the X-2 Penetration is successfully made and the follow-on survey to investigate the condition inside Primary Containment is also successfully done, establishing an access route for the future debris retrieval from the Pedestal region is a different story.

Progress in the Past and Plans for the Future

According to the presentation material “Status of Interference Removal Activities as a Support for the Unit 1 PCV Internal Survey” dated 29 October, 2020, prepared by Tokyo Electric Power Company Holdings, a penetrating hole must be cut into both Inner Door and Outer Door on the X-2 Penetration (Personnel Airlock), to have the Inspection Unit required for inspecting conditions inside the Primary Containment be inserted, also to have tools necessary to remove interfering items get an access. A set of equipment consists of Cable Dram, Shield Box, Isolation Valve, Connection

Duct, Guide Tube, Installation Tool and Inspection Equipment in inward direction must be installed. The Guide Tube penetrates both Inner Door and Outer Door of the X-2 Penetration.

The project to cut holes on doors started at the site on 8 April, 2019. First, on the Inner Door. A high-pressure Abrasive Water Jet (AWJ) was selected for this project. The team started up the AWJ machine on 4 June, 2019 to cut a 210mm diameter hole. The airborne level inside the Primary Containment was monitored during this cutting process, and soon reached to the control level of 1.7×10^{-2}Bq/cm^3. The cutting work was halted and resumed as the airborne level was closely being monitored. Finally, cutting a hole in the Inner Door was completed on 22 April, 2020. Then, the grating floor, one of the interference items, was cut on 25 August. The team proceeded to cutting the steel member underneath the grating floor by applying the AWJ method. However, they experienced a problem with the abrasive feeder and halted the work on 4 September during the work. On 28 September, the team was ready to resume the cutting work. However, they noticed that there was an instrument line for the Reactor Recirculation System in the vicinity of the work area where the cutting work was on going. The team decided to stop cutting again and changed the plan. They selected another location. Accordingly, they will cut different steel members, electrical conduits and handrails one by one in parallel with cleaning per new plan.

When all of these preparation works have been done, the X-2 Penetration Airlock Doors will have three Guide Pipes. The team will use them to insert the PCV Internal Inspection Equipment which is integrated with an ROV for inspection.

The original plan per NDF's Technical Strategic Plan dated 2 October, 2018, showed that activities such as inspections to assess the conditions of structures and the distribution of deposits outside Pedestal as well as sample-taking were scheduled to begin in the first half of FY2019. TEPCO's presentation material outlined above reflected the delays and changes occurred thereafter.

Fuel Debris Retrieval

As already discussed in detail above, the availability of X-6 Penetration for the fuel retrieval is and will be unknown at least for the time being for Unit 1. Therefore, there is no prediction when the fuel debris retrieval would begin. There has been no start to any assessment inside the Primary Containment through the X-2 Penetration. It is assumed that a small amount of fuel debris remains inside the Reactor Pressure Vessel, and much of the fuel debris that drained down to the Pedestal region spilled out through the personnel opening to cover the Drywell floor. If the intended retrieval should cover wherever the fuel debris spreads, the justification of the choice of, and the feasibility of, the "Dry Lateral Access" approach by using a robot arm becomes questionable.

Especially in case of Unit 1, the failure of the Reactor Pressure Vessel bottom head occurred in a very early stage before any effective attempt to inject cooling water. The hot molten fuel debris drained down to the Pedestal region must have filled two drain sumps on the floor and eroded deeply into the concrete. Accessibility to these locations by the "Dry Lateral Access" approach also seems to be very difficult.

2.3.5 Plan-B at Risk of Abandonment

In the "Fukushima Closure Plan" which the author of this report prepared and submitted to IRID in October 2013, constructing a moat around the entire site to convert to the "Dry Island" was proposed as a passive and permanent countermeasure against the issue of contaminated water. And as a cooling method for the fuel debris, changing from water cooling to air cooling was proposed. Lastly, as an alternate method to retrieve the fuel debris, a concept to install an underground hot cell was proposed. The radiological environment of the general work area outside the hot cell is much better than that of the Reactor Building, so that workers do not need to limit their work hours because of radiation exposure, do not need wear heavy protective clothing to protect them from contamination, and do not need to wear respirators to protect them from high level airborne radioactive material. The retrieval machine is installed inside the hot cell and fully remotely operated by an operator in the workstation outside the hot cell. The retrieval machine extends the telescope arm upward along the center axis of the Pedestal and the Reactor Pressure Vessel (See conceptual sketches below for each feature mentioned above).

For comparison, the methodology which the NDF team, mainly TEPCO engineers, has been pursuing to date is outlined as follows. In 2018 TEPCO finally decided to abandon the orthodox approach, “Flooded Top Access” and change to the new concept of “Dry Lateral Access”. The frozen wall designed to isolate the groundwater flow leaking into the buildings did not meet the original expectation to mitigate the contaminated water issue. Water has been continuously injected into the Reactor Pressure Vessel to remove the residual heat generated by the fuel debris. However, this water injection, along with the groundwater leakage into the building, has been the root cause of the ever-growing contaminated water issue. Although NDF recognizes that the water injection is one of the root causes, they have been reluctant to treat this matter seriously and have not decided yet whether they should terminate it or continue. Their fuel debris retrieval strategy by using “Dry Lateral Access” does not seem to have a bright future, either. Many known and unknown difficulties lie ahead. The author grouped all of these features above together and called it “Plan B” as a whole. However, the reality is that none of these selected technologies (contaminated water, fuel debris cooling and retrieval) looks technically sound, reliable, sustainable or practical.

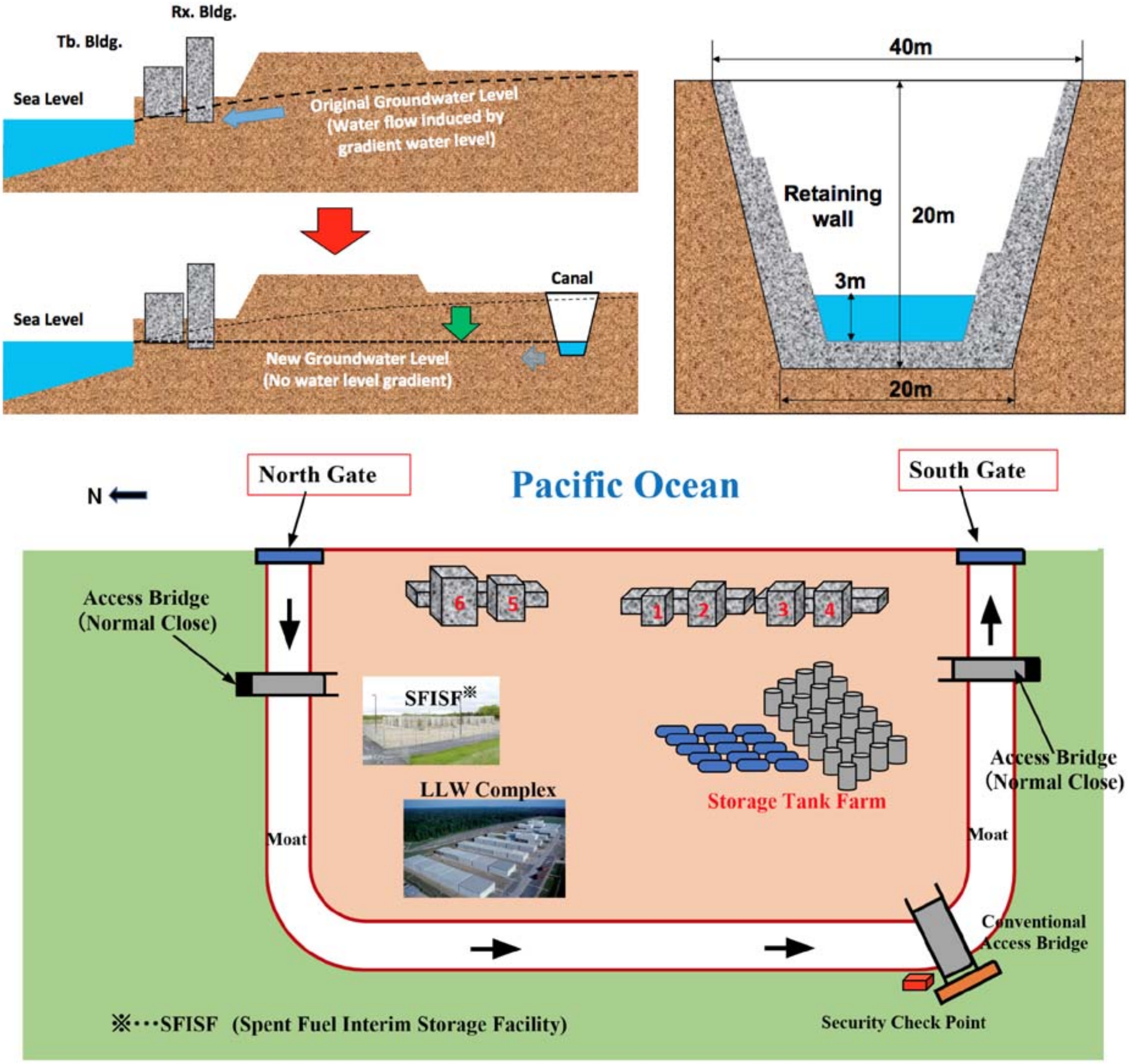


Diagram 4: Concept of Moat proposed in “Fukushima Closure Plan”
(Source: Author)

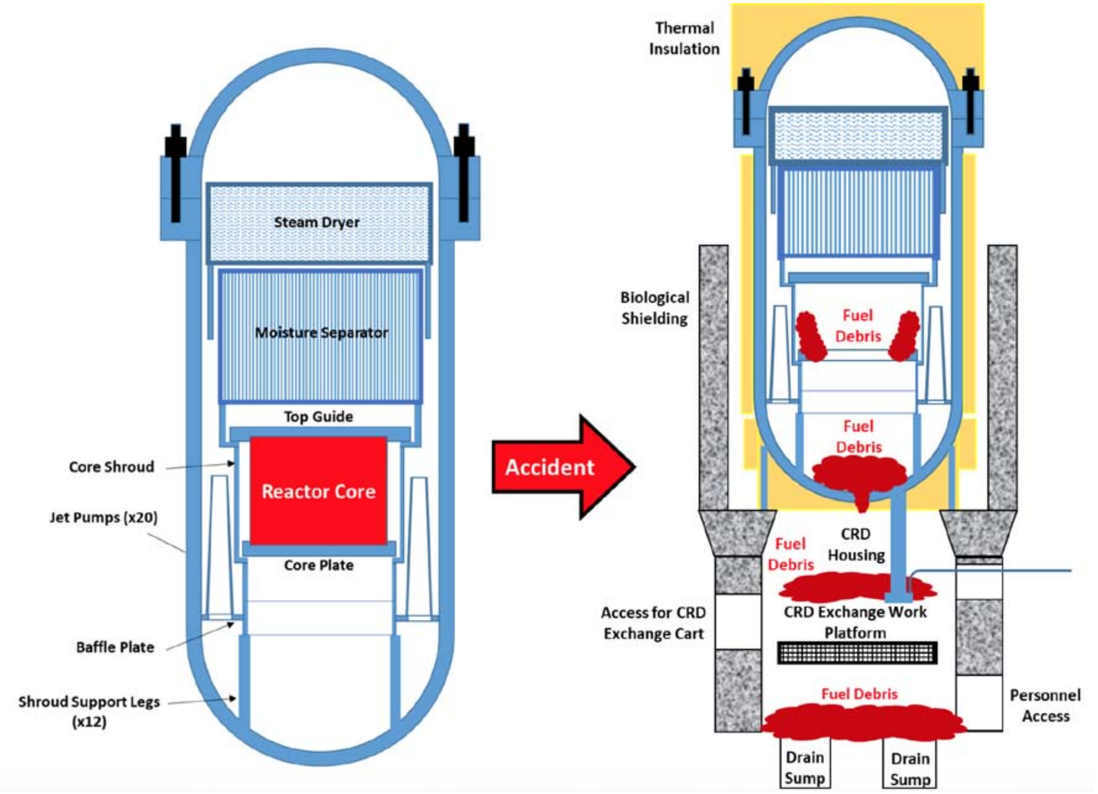


Diagram 5: Distribution of Fuel Debris assumed in “Fukushima Closure Plan”
(Source: Author)

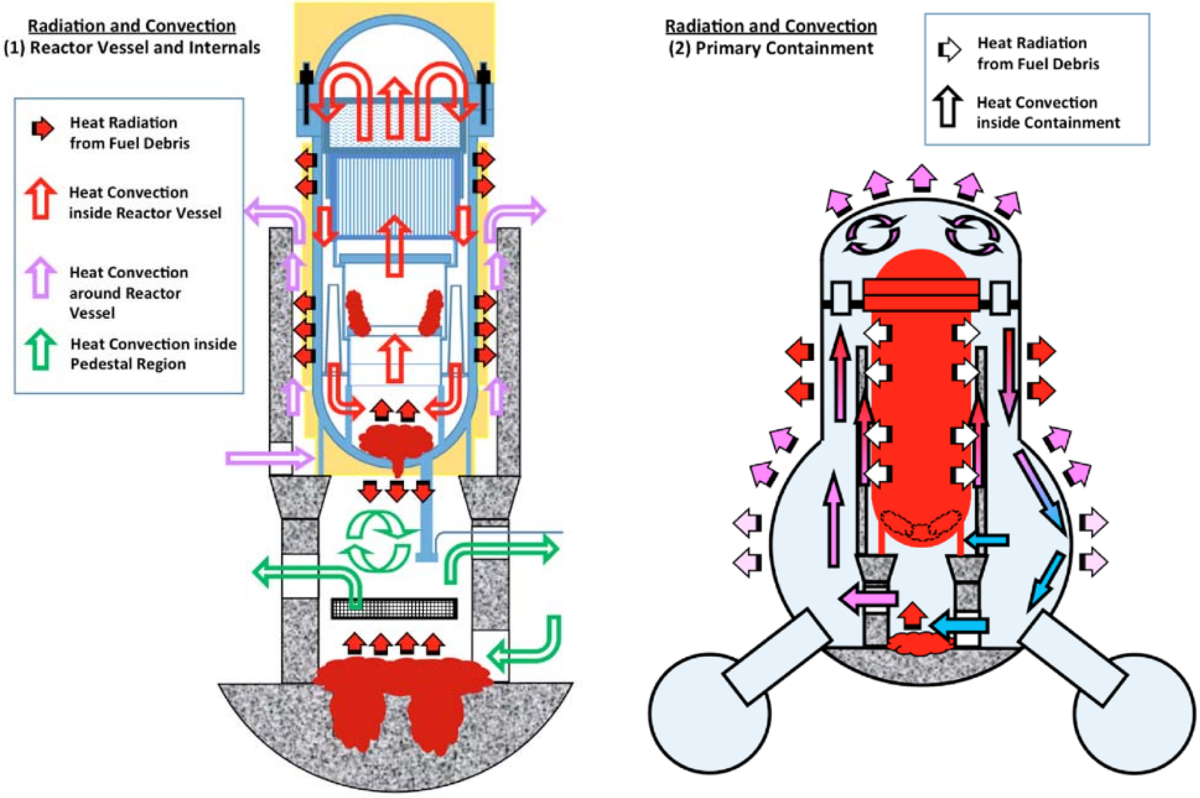


Diagram 6: Heat Convection and Radiation considered in “Fukushima Closure Plan”
(Source: Author)

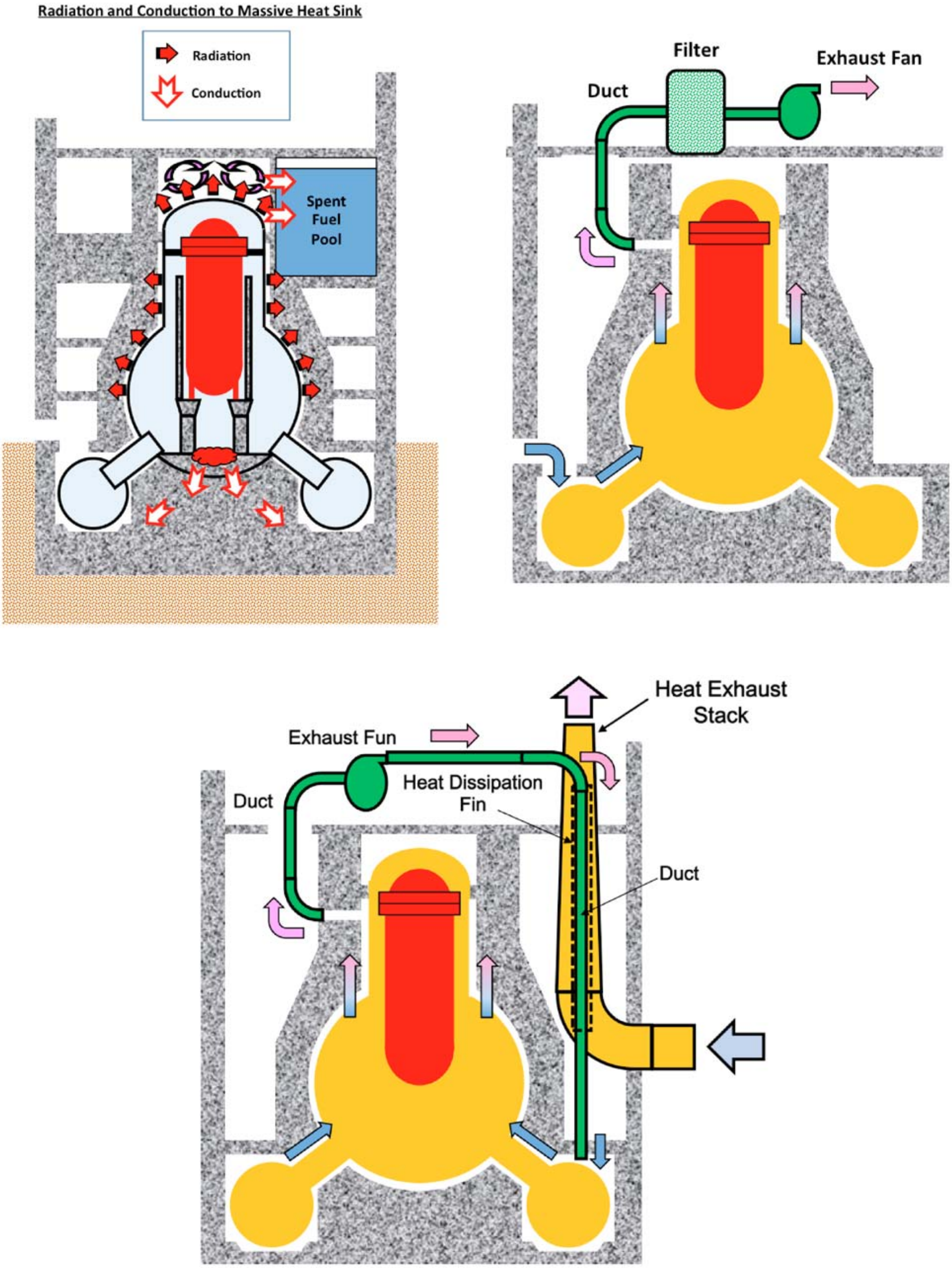
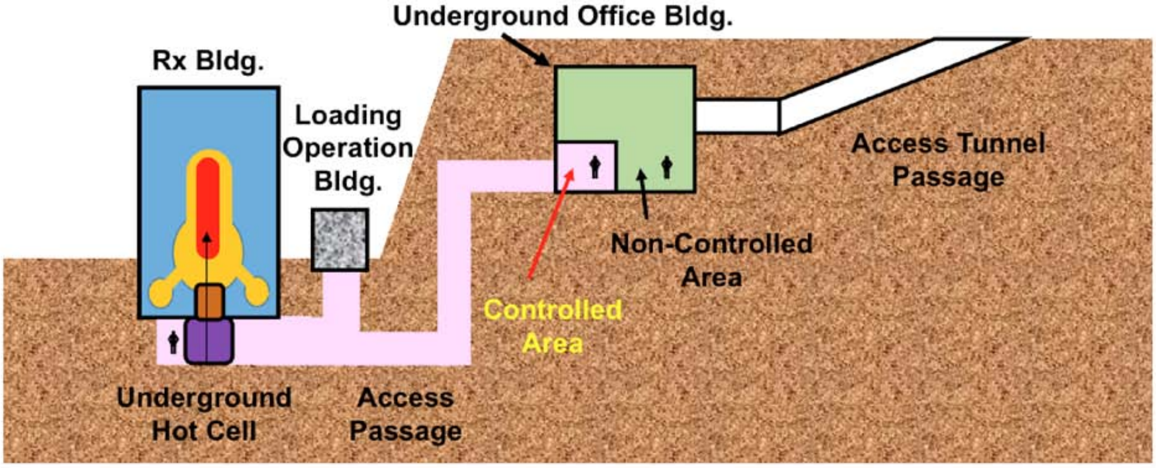


Diagram 7: Concept of Heat Dissipation from PCV considered in “Fukushima Closure Plan”
(Source: Author)



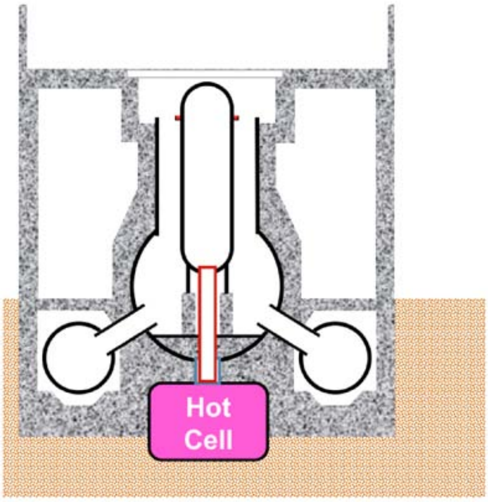
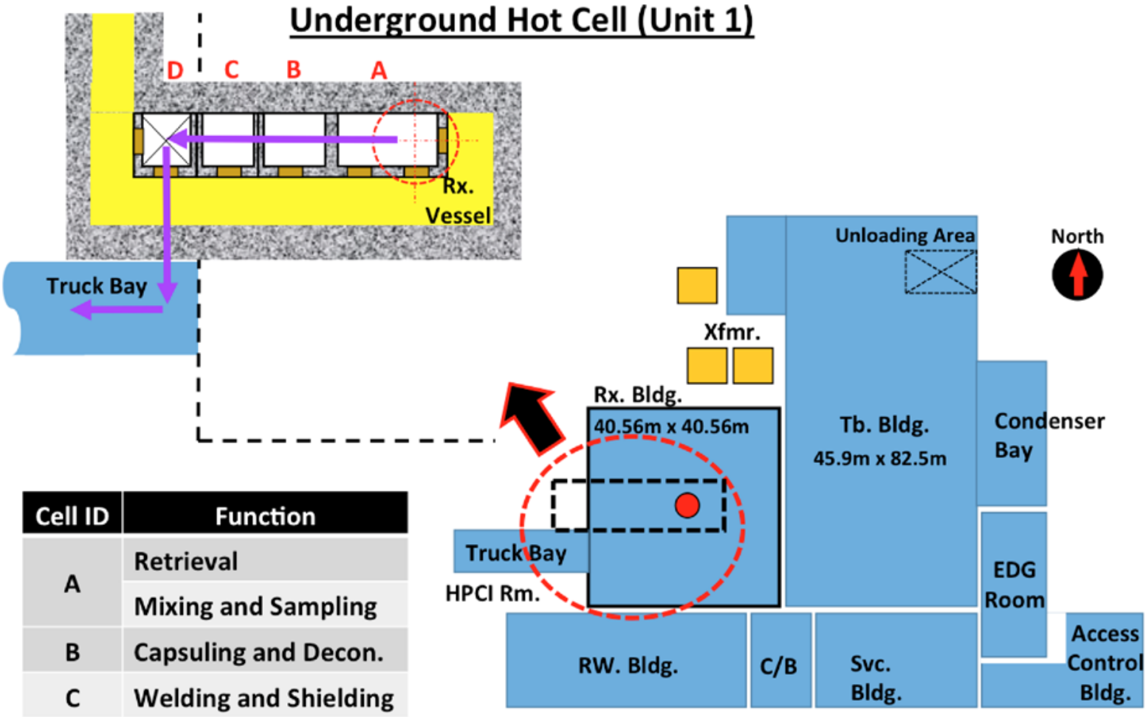


Diagram 8: Concept of Underground Hot Cell proposed in “Fukushima Closure Plan”
(Source: Author)



Cell ID	Function
A	Retrieval
	Mixing and Sampling
B	Capsuling and Decon.
C	Welding and Shielding
D	Access

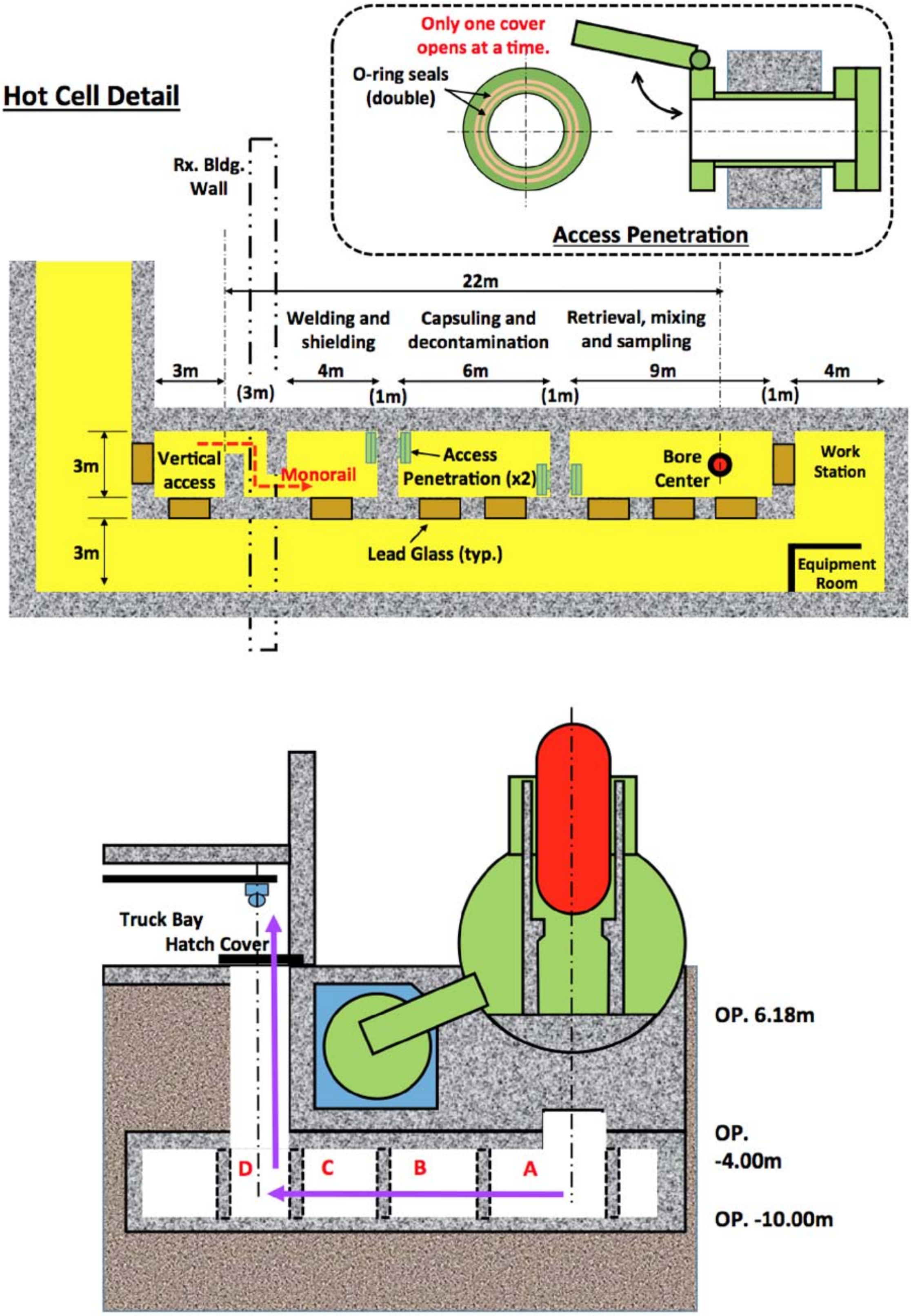
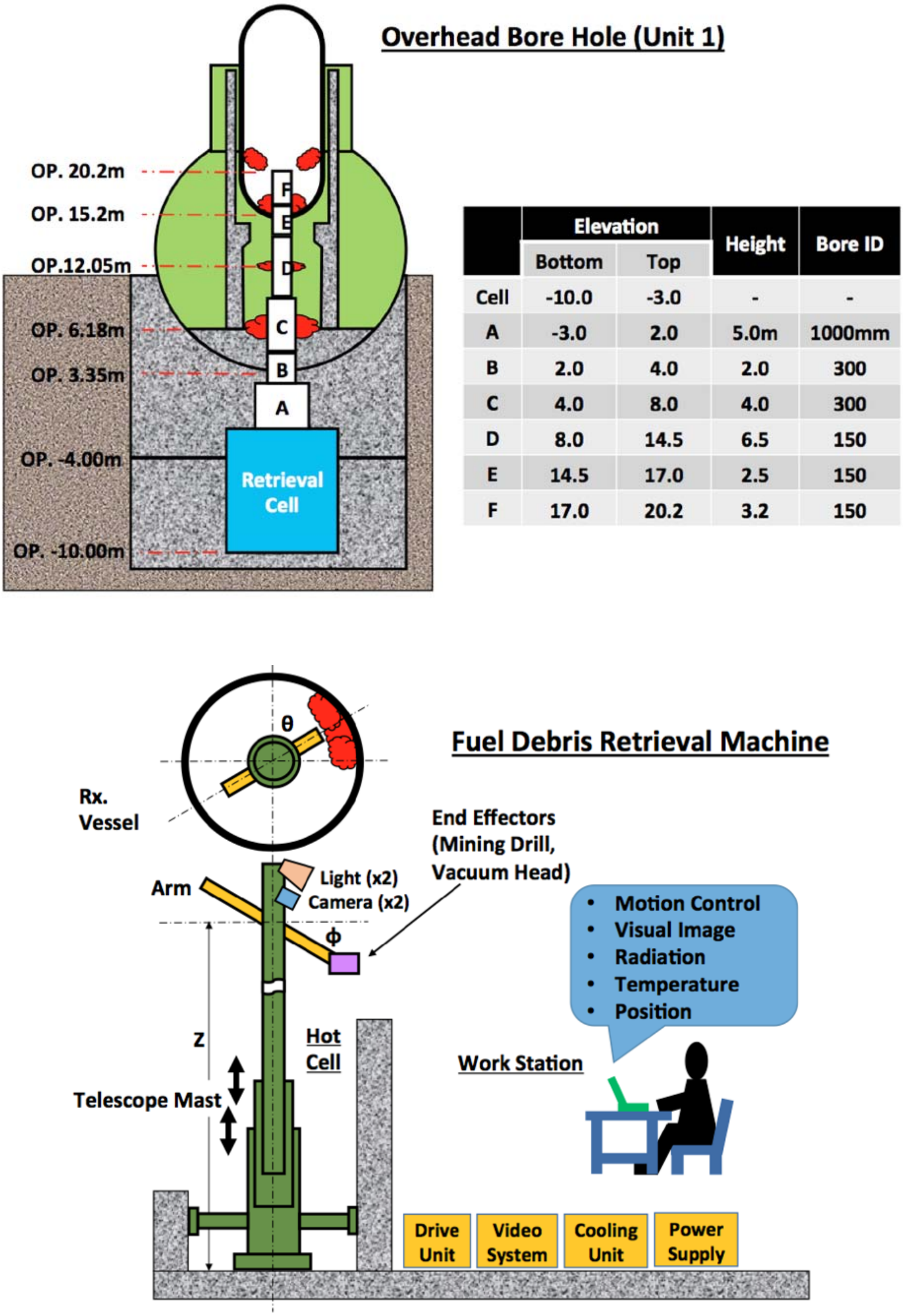


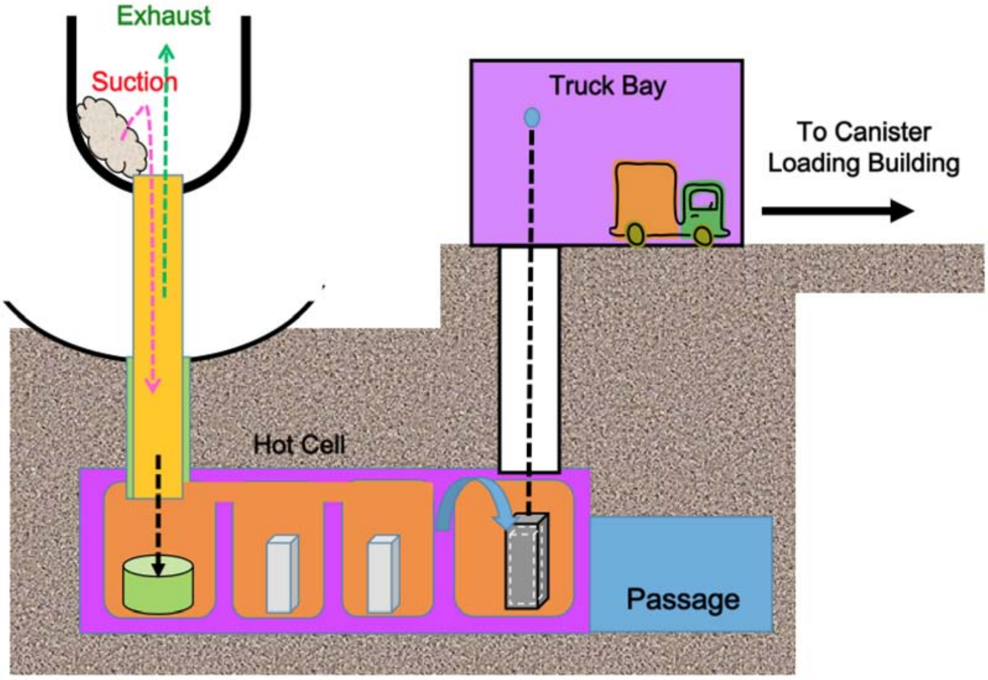
Diagram 9: Detail of Underground Hot Cell proposed in “Fukushima Closure Plan”
(Source: Author)



- Motion Control
- Visual Image
- Radiation
- Temperature
- Position

	Elevation		Height	Bore ID
	Bottom	Top		
Cell	-10.0	-3.0	-	-
A	-3.0	2.0	5.0m	1000mm
B	2.0	4.0	2.0	300
C	4.0	8.0	4.0	300
D	8.0	14.5	6.5	150
E	14.5	17.0	2.5	150
F	17.0	20.2	3.2	150

Diagram 10: Concept of Fuel Debris Retrieval from Hot Cell proposed in “Fukushima Closure Plan”
(Source: Author)



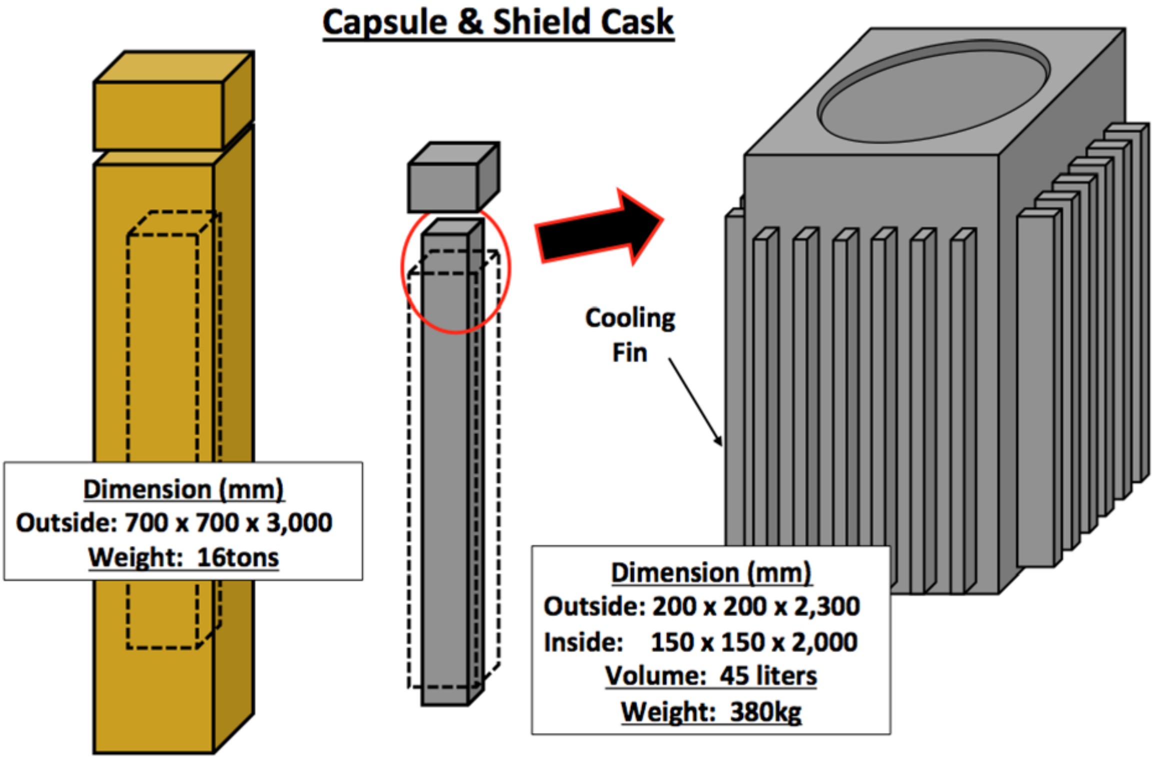
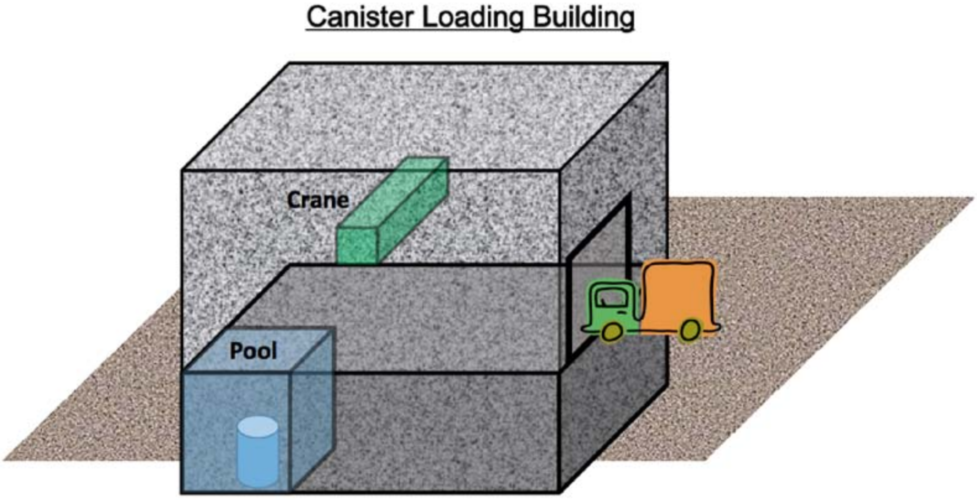


Diagram 11: Concept of Capsule and Shield Container to be used for transportation of Fuel Debris proposed in “Fukushima Closure Plan”
(Source: Author)



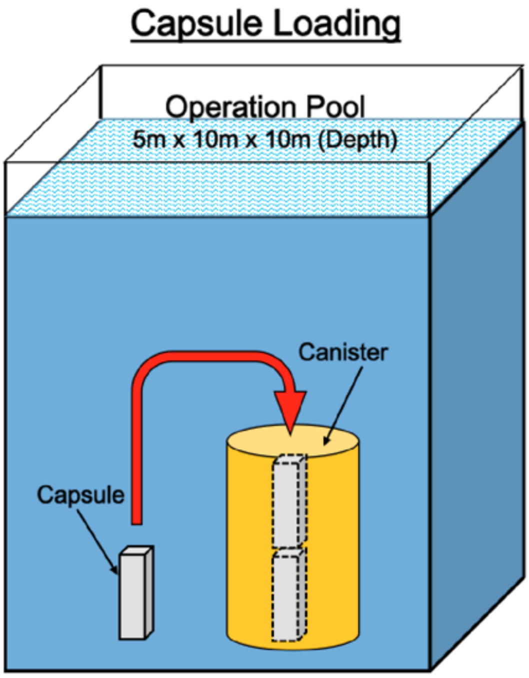
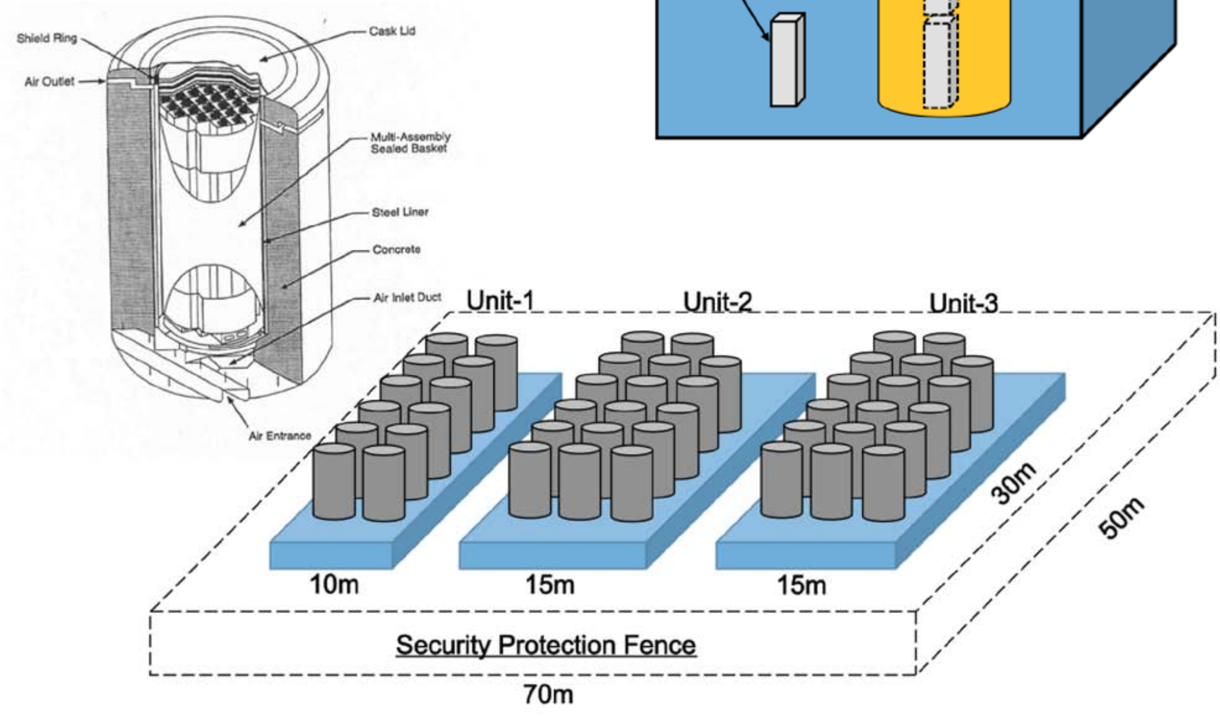


Diagram 12: Capsule Loading in Casks and Cask Storage proposed in "Fukushima Closure Plan"
(Source: Author)



Fuel Debris Cooling

Although NDF never explained explicitly, they may have a good reason to be reluctant to change from water cooling to air cooling of the fuel debris. It is predictable that the fuel debris once dried by the residual heat would generate dust particles. The radioactive material would be carried airborne by the convection flow entirely inside the Primary Containment, including the space inside the Torus (Suppression Chamber) through Vent Pipes after draining water, contaminating all exposed surfaces of equipment and structures. Such radioactive material becoming airborne would include nuclides of alpha emitters that are also categorized as the fissile material. They are specifically radioactive isotopes of Plutonium (Pu-238, Pu-239, Pu-240, Pu-241), Americium (Am-241, Am-242, Am-243) and Curium (Cm-242, Cm-243, Cm-244). Each of these nuclides would cause a variety of problems depending on their chemical, physical and radiological properties.

Firstly, the radio-toxicity of alpha emitters is much higher than that of beta nuclides, their accurate measurement is more difficult and much more rigorous control is required for protecting workers from the potential acute and delayed health impacts. For example, a special instrument such as ZnS (Ag) scintillation counter instead of a conventional GM-counter is required to detect and measure the alpha emitting nuclides for monitoring the work environment and a different technique such as bioassay instead of a conventional whole-body counter is required to detect and measure the body burden. Secondly, the procedure to handle the radioactive waste contaminated with alpha nuclides becomes more complicated than that without alpha nuclides, depending on the density. In an extreme case, it will be considered to fall under the category of Greater Than Class C (GTCC) so that the ordinary near-surface disposal is not possible. Lastly, since the alpha nuclides of concern are fissile materials, a rigorous traceability control is required for each nuclide.

There is a risk of producing airborne radioactivity just by drying the fuel debris. If it is aggressively cut or ground in air for retrieval, the level of such a risk would be significantly increased.

Is cutting or grinding the fuel debris underwater for retrieval a better approach? Such an operation would produce tons of small particles, then they would release much water soluble and insoluble radioactive material including alpha nuclides in water. If the fuel debris would be cooled with water in parallel with this operation, it would contaminate the water treatment system entirely. Producing highly concentrated contaminated water would continue as long as this operation continues. It should be also noted that the cooling water contains some dissolved air because the system does seem to have deaeration equipment in the recirculation loop. Although the atmosphere inside the Primary Containment is inert, cooling water containing some oxygen and carbon dioxide may not be sufficiently inert for the unprotected steel and concrete surfaces.

In summary, both cooling the fuel debris with air and cooling with water have different types of inherent disadvantages. However, it is essential to change from water cooling to air cooling in order to terminate the further production of contaminated water.

Method for Fuel Debris Retrieval

“Dry Lateral Access”, the fuel debris retrieval method that NDF has been pursuing, utilizes the X-6 Penetration as an access point and a robot arm for activities inside the Primary Containment. This method may work for the pilot demonstration at Unit 2. However, considering various difficulties described below, whatever lessons the NDF team would learn, they would not assure success for the full-scale production.

It is relatively easy to remove the fuel debris sample from inside of the Pedestal. In reality, however, the fuel debris might have been fused with the bottom of the Reactor Pressure Vessel and some of the Reactor Internals. Likewise, the fuel debris drained down from the failed bottom head of the Reactor Pressure Vessel might have been sprayed over and trapped within crevices and other complex geometries formed by the components such as CRD Housings, CRD Restraint Beams and many other associated accessory parts, as well as non-Reactor hardware such as the grating floor and the cable trays of the CRD removal and installation work platform. Also, it should be noted that while most fuel debris stayed within the Pedestal region, some portion of it flowed out through the personnel access opening on the bottom and spread over the Drywell floor. The Pedestal wall and floor, and Drywell floor are all made of concrete. When the molten Core, or so-called “corium”, a mixture of molten metal and uranium oxide, melts the concrete as it flows, it forms lava. A large amount of solidified rocky lava was discovered at Chernobyl Unit 4 and named “Chernobylite”. Something similar to Chernobylite might have been formed wherever the molten corium flowed and touched during movement in Fukushima Units 1 to 3. Other portion of molten corium filled the sump pits and might have eroded deeply downward. If all of this must be removed, the robot arm must be given many joints and degrees of freedom. However, even if it is designed and constructed in that way, there is no assurance it would work as intended. To increase the level of reliability, the prototype tool must be constructed and a full-scale mockup demonstration for all conceivable geometries and configurations must be conducted with successful results prior to the deployment in the affected plants. In addition, for the reasons below, some extra difficulties are anticipated for the access into the Reactor Pressure Vessel and the fuel debris retrieval activities inside after that.

No attempt has been made to view upwards by using the camera inside the Pedestal simply because it was not designed to do so. Therefore, there is no information even for guessing the location, number, shape and size of openings where the fuel debris drained out. The NDF team guesses that there must be multiple openings because water is dripping from multiple locations. They may or may not be correct. There are too many components forming complicated network between the bottom head and water surface so that the number of water-dripping points and the number of openings is not the same. However, one thing we know for sure is that at least one opening is large enough to allow the Upper Tie Plate to go through. There may a lot more hanging in air. As illustrated in the sketch below, components and structures such as CRD Housings, ICM Housings and CRD Restraints located underneath the Reactor Pressure Vessel must have undergone a significant deformation due to the mechanical and thermal load caused by the fuel debris flow. For a robot arm to reach the opening, it would need to trace the complicated 3-D orbit instead of a simple straight line.

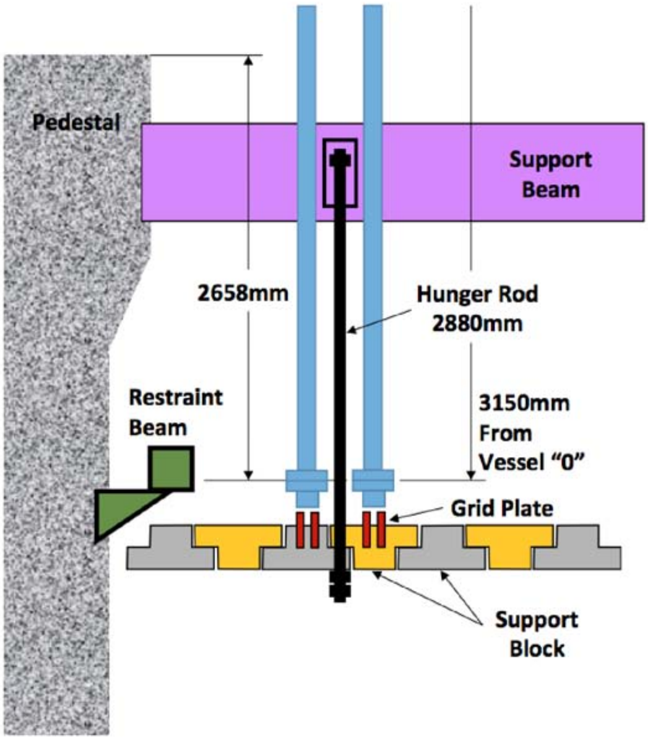


Diagram 13: Complexity of Under-vessel
(Source: Author)

- Even if the difficulty of accessibility mentioned above is somehow overcome and the robot arm finds a way to go inside the Reactor Pressure Vessel, there may be more difficulties waiting. Geometries of the bottom head interiors and remnants of the Reactor Internals resting there are unknown. How and where the residual fuel debris is trapped, adhered to and fused are all unknown. Some fuel debris might have migrated into narrow crevices inside CRD Housings, ICM Housings and the Bottom Head Drain nozzle. Wherever it spread around and penetrated, the cutting bit and/or the grinding stone must somehow access there to be effective.
- Distributions of the fuel debris inside the Reactor Pressure Vessel and the Primary Containment are assumed to vary among the affect units. Unit 1 is expected to have a lot of “Chernobylite” like rocks to be excavated, while Unit 2 is expected to have a good portion of the fuel debris remaining inside the Reactor Pressure Vessel and Unit 3 is expected to have both, more or less.
- Efforts made so far to characterize the property of the fuel debris were limited to the top of the deposit inside the Pedestal region. The NDF team concluded that it was in the pebbly, sandy and clay form. However, there could be larger chunks embedded in the molten metal, concrete or a mixture. A thick layer of large mass, something similar to “Chernobylite”, could be on the bottom.
- It is necessary to set up a facility consisting of various pieces of equipment including a Shield Box in the vicinity of the X-6 Penetration. However, the dose rate in the work area indicates the required activities risk too much radiation exposure to workers.

In the author’s opinion, based on all factors above evaluated collectively and relatively, NDF’s “Dry Lateral Access” approach does not appear to be superior to “Fukushima Closure Plan”.

The frozen wall, in comparison with the concept of moat, is less effective to isolate the groundwater flow and more costly. It should be noted that because the frozen wall is not a passive design like the moat, it would require additional cost and personnel resources for operation, monitoring, inspection and maintenance after completion. These activities cost radiation exposure as well. There is no added value like those available in case of moat design (These are not mandatory but optional, but once “Dry Island” has been completed, taking an advantage of the lowered groundwater level, underground trenches can be constructed to store the low-level radioactive waste. The moat can be also used as a robust security boundary).

The Shield Box proposed under the current Plan B to be installed on the first floor of the Reactor Building seems to be less costly compared to the Hot Cell installed underground. However, the radiological environment in the vicinity of the installed Shield Box will be severe even in Unit 2, worse in Unit 3 and worst in Unit 1. The workers would be required to wear heavy protective anti-contamination clothing and full-face respirators. They would be required to go through an extensive training program to be qualified for operation and maintenance of the robot arm before taking the assignment. However, they would not be able to stay so long at the site because of the limitation of radiation exposure.

For the robot arm to enter the Reactor Pressure Vessel inside through the X-6 Penetration to retrieve the fuel debris, unlike the telescope mast axially extendable along the centerline of the Reactor Pressure Vessel and the Pedestal which is rotationally symmetric, it must have many joints and degrees of freedom allowing to travel along a complicated 3-D orbit. This seems to be far beyond what the current robot arm technology can handle.

Even though there seems to be more chance for the simpler telescope mast design to work better for retrieving the fuel debris, the author must admit that there is not enough confidence to gain sufficient coverage after reviewing many conceivable configurations as discussed above. On the other hand, the author is encouraged by the recent rapid advancement of other areas of robot technology in the last 7 years since submitting the “Fukushima Closure Plan”. By extrapolating such an advancement for the next several decades, it is expected that the technology would become sufficiently matured to be applied for the fuel debris retrieval. Rather than strategizing with a combination of premature technologies at this moment, we could explore a different avenue. The author calls this “Plan C” and will discuss it in detail in the later section.

2.4. Waste Management On-site / Off-site

The reason for choosing the frozen wall was explained in 2013, an ability to fully restore to the original condition by not leaving any permanent structure underground was the strong point emphasized as a political justification. This explanation derived an impression as if all buildings on the site whether above the ground or below the ground would be eventually removed, and that any other option not consistent with this basic requirement is not acceptable. However, if there is such a basic requirement at all, the waste management plan that NDF is pursuing looks contradictory because TEPCO has been constantly expanding the infrastructure on site, and do not appear to be interested in returning most, if not all, of the space to the green field.

Specifically, as indicated in the waste storage plan outlined below, TEPCO will aggressively continue to build large storage facilities, which looks like a permanent structure complex. If they are really and seriously trying to achieve the green field, at least the same amount of waste generated on site must be eventually carried out to a disposal site. Otherwise, they should maximize the use of open space already available in the existing buildings such as the turbine buildings, instead of constructing new buildings.

The fact that they do not seem to be serious in making such an effort could be interpreted as an unsaid and an unstated decision not to pursue the green field as an ultimate goal for the decommissioning. Because NDF is operated by the public fund, their intention must be fully transparent to the public. If green field is no longer a goal for NDF and METI, they should explicitly make a statement in the Technical Strategic Plan and the Road Map respectively. After all, turning to green field is an unrealistic groundless 10-year-old overcommitment. This should have been obvious simply based on the level of soil contamination. Once this reality has been publicly admitted and agreed, the entire decommissioning project would become more flexible, efficient and cost-effective. The number of storage building to house low level radioactive wastes could be minimized by constructing storage trenches if the “Dry Island” concept is implemented and the groundwater level is lowered to the seawater level.

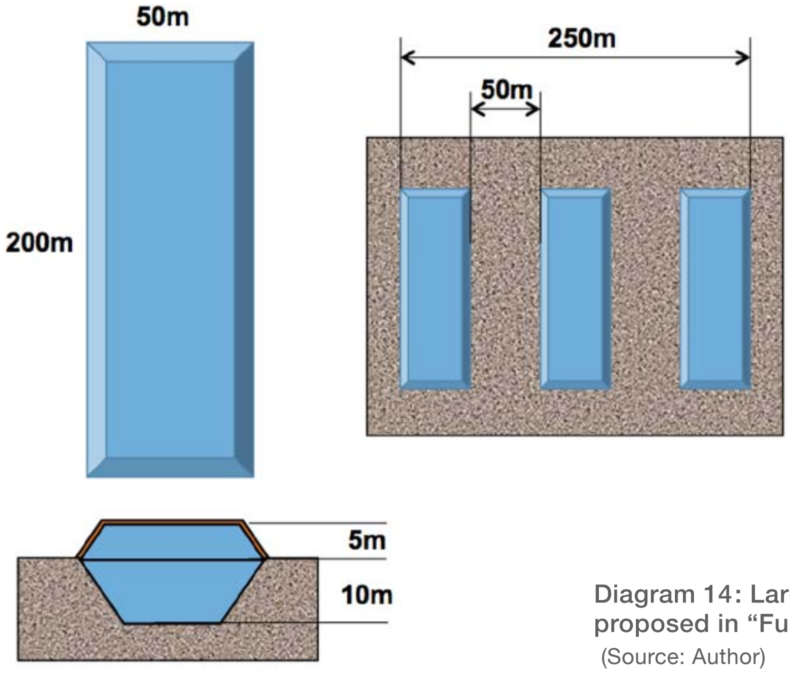


Diagram 14: Large Waste Disposal Trench proposed in “Fukushima Closure Plan”
(Source: Author)

2.4.1 Plan for Waste Storage in Fukushima Daiichi

According to TEPCO's presentation material "Fukushima Daiichi Nuclear Power Station Management Plan for Solid Waste Storage - FY2020 Revision" dated 14 September, 2020, in addition to the existing Solid Waste Storage Buildings No.1 through No.8, 9th Building was put into service from February 2018. Also, constructions of 10th and 11th Buildings, or so-called Annex Solid Waste Storages will be completed after FY2022 and put into service.

Of this material, the projected total volume of radioactive waste generated in Fukushima Daiichi Nuclear Power Station by March 2032 is estimated to be approximately 784,000m^3. Out of this total volume, approximately 203,000m^3 is indicated to be recyclable, and remaining 581,000m^3 is subject to storage at the site after processing to reduce the volume. TEPCO estimated that it would be reduced down to 261,000m^3.

The recyclable waste is limited to the one below the threshold level of 0.005mSv/h and mostly consists of the water storage tanks (approximately 62,000m^3) assuming they are emptied and disassembled by then, HIC Stainless Steel Armors, "Blue Tanks" after decontamination and Steel Scraps. It is expected that these account for 141,000m^3.

For the purpose of volume reduction for the miscellaneous combustible wastes such as trees cut down to expand the tank farm and used protective clothing, under the plan an incineration facility is to be used. The construction is expected to complete within FY2020. This is intended to reduce the volume. TEPCO estimates that the preprocessed volume of 274,000m^3 will be reduced to 21,000m^3. For the miscellaneous non-combustible waste, the construction of the other type of volume reduction facility equipped with concrete crushers and metal cutters is expected to complete within FY2022. 136,000m^3 of the estimated volume generated is to be reduced to 69,000m^3.

Under the category of non-compressible radioactive waste, approximately 53,000m^3 of contaminated soil is included. It will be packed in metal containers and stored in the 10th storage building (capacity: 80,000m^3). Some part of the contaminated metal / concrete debris above the threshold level (118,000m^3) is presently stored in containers, but the remaining part is stored on the yard by covering with plastic sheet or buried in the temporary facility. These will be eventually stored in 10th and 11th storage buildings (capacity: 115,000m^3). By accomplishing these activities, all waste currently stored outdoors will be moved indoors by FY2028, so that the risk of spreading contamination will be permanently mitigated.

The secondary waste generated by operating the water treatment system composed of the chemically precipitated deposits and spent adsorbent of ALPS (approximately 6,200 units) will be stored in the Large Waste Storage, separately from the Annex Solid Waste Storages mentioned above. The construction is currently in progress and the completed storage will be put into service in FY2021.

If we try to visualize the overall landscape of Fukushima Daiichi Nuclear Power Station around 2032, we will quickly realize that there are many large facility buildings still standing on the site. Including not only Reactor Buildings and Turbine Buildings of all Units 1 through 6, Process Main Building, High Temperature Incineration Building, but also 11 large solid waste storage buildings and the Large Waste Storage additionally constructed. More buildings will exist than before the accident. The welded type tanks whether still containing the treated water or already emptied by then, may or may not still be on site as well.

If these remaining Reactor Buildings and Turbine Buildings are dismantled during the next 20 years, what benefits can be expected? More work simply generates more waste, which requires more storage facilities.

2.4.2 Waste Volume Generated from Decommissioned Nuclear Power Plants

In the main text of the WNA document, "Methodology to Manage Material and Waste from Nuclear Decommissioning" prepared by its Waste Management & Decommissioning Working Group, published in February 2019, the volume of waste generated by decommissioning a German BWR plant, Wrasse Nuclear Power Plant (Net Capacity: 640MWe, Commercial Operation Period: 11 November, 1975 to 26 August, 1994) is mentioned as an example. The following is the rough breakdowns of the waste according to this information.

- Unconditionally Released:
  255,500 tons
- Conditionally Released for Recycling:
  3,000 tons
- Radioactive Waste:
  4,600 tons

Unless there is any major trouble or accident throughout the operation history, most debris generated by dismantling the reinforced concrete structures of Reactor Building and Turbine Building can be unconditionally released as illustrated above. And the amount of waste is as much as 250,000 tons per unit.

Also, in Appendix 6 "Decommissioning Waste Management in Spain" in the same WNA document, more detail information is presented for the Spanish plant, José Cabrera Nuclear Power Station (frequently called "Zorite"). This is a small Westinghouse PWR plant (Net Capacity: 141MWe, Commercial Operation Period: 1969-2006). Decommissioning activities began in 2010. Originally, it was supposed to be completed by 2016, but dismantling continued until 2018. This was then followed by the site remediation and confirmation. The amount of waste generated as a result of decommissioning activities is as follows:

- Concrete Debris
  95,300 tons (Used for Reclamation)
- Steel Scraps
  4,700 tons (Recycled)
- VLLW, LLW, ILW
  4,000 tons (Transferred to ENRESA)
- Spent Nuclear Fuel
  175 tons (ISFSI)
- Reactor Internals
  43 tons (ISFSI)
- Hazardous Waste
  Small Amount

Based on the information above, roughly 1.5 to 2 million tons of concrete debris and steel scraps is expected to be generated by dismantling Units 1 to 6 of Fukushima Daiichi Nuclear Power Station. Even though most of them could be radiologically clean, because, unlike ordinary decommissioning plants, these units have been exposed to waterborne and airborne radioactivity, they should be conservatively assumed to be contaminated. In order to unconditionally release a part of them, screening by a high-sensitive instrument for all potential contamination nuclides, including alpha emitters, much be carefully and accurately practiced under very low background. Otherwise, any partial elimination must be technically justified. Again, the amount to be processed is approximately 1.5 to 2 million tons in total. It would take 10,000 days (~30 years) even if 150 to 200 tons are screened daily. Furthermore, unless their recipients are designated and methods of transportation are determined in advance, they are not permitted to be transported offsite.

It looks totally impractical to dismantle all existing buildings resulting in countless pieces of concrete debris and steel scraps, then to screen them piece by piece for unconditional release, and finally to transport them by trucks or ships to be recycled. And it should be noted that this is still not the end of the green field decommissioning scenario. There is an enormous amount of contaminated soil. The contamination nuclides must have spread broadly over the ground surface by wind (airborne) and seeped deeply into the soil by rain and carried by groundwater along the water table (waterborne).

The Japan Nuclear Fuel Limited (JNFL) owns and operates a facility for low-level radioactive waste disposal in Rokkasho Village, Aomori Prefecture (Low Level Radioactive Waste, LLW, Disposal Center). The capacity of the Center can be ultimately expanded up to 600,000m^3, however, it currently operates only two disposal facilities, namely No.1 and No.2. Their capacity is 40,000m^3 each. JNFL has a plan to construct the third facility (No.3) with a design capacity of 42,000m^3. Since the facility is intended to be available for all nuclear utilities in Japan, only decommissioning project of Fukushima Daiichi Nuclear Power Station. should not monopolize the use of the facility. However, even if such a decision was made it is not possible for the Rokkasho LLW Center to manage the volume of waste planned to be generated at Fukushima Daiichi anyway. In reality, there is no place outside of the Fukushima Daiichi Nuclear Power Station for the contaminated soil to be received.

Without a location somewhere in Japan that is capable of receiving the enormous amount of radioactive waste already existing and that to still be generated, the proposal to turn the entire site of Fukushima Daiichi Nuclear Power Station into a vast green field site, one with no structures and ready to be used for any purpose without any restriction or condition is a hopeless dream through the remainder of this century.

There is no cost-benefit justification or incentive to invest valuable resources in trying to do so. It is time to rethink the approach and to abandon the unreasonable expectations created not through science and engineering assessments by politics and emotionally induced by an impractical overstatement 10 years ago.

The importance of “speediness”, one of five basic attributes mentioned in the Medium-to-Long Term Road Map by the government and NDF’s Technical Strategic Plan should be reconsidered. It is necessary to rethink and replan the entire program from the viewpoint of practicality and achievability and based on technical and economical feasibility for a long term, 100 year plus timeframe. Following such an approach, the author believes that the concept of isolating the site by constructing a moat converting the site to a “Dry Island” would advance us towards a common goal more efficiently, effectively, safely, economically.

2.4.3 Wastes other than Fuel Debris

As described in NDF’s Technical Strategic Plan 2020, the zeolite sandbags left on the basement floors of Process Main Building and High Temperature Incineration Building were found in December 2019. They read as high as 3Sv/h and 4Sv/h respectively on contact. NDF states that the problem of how to retrieve them suddenly surfaced upon this discovery. However, there are many other radioactive wastes that are difficult to retrieve and handle in addition to the high radiation zeolite sandbags.

For example, in the Spent Fuel Pools of Units 1 to 6, there are typically many high radiation components and wastes other than spent fuel assemblies such as spent (depleted) Control Rods, In-Core Neutron Monitors, Startup Neutron Sources and spent filter units used to vacuum high radiation sludge. In the Radwaste Facility, there are storage tanks containing high radiation filter sludge and spent resin. And in the Common Pool, many spent fuel assemblies, Control Rods and Channel Boxes are stored. Reactor Internals Replacement projects were performed for Units 1 to 3 and 5 since late 1990’s. Most of the irradiated Reactor Internal components such as Core Shroud, Top Guide, Jet Pumps have been removed, sliced to smaller pieces, loaded in the basket and stored in the Common Pool underwater. In the midst of the same project for Unit 4 on 11 March, 2011, Fukushima Daiichi Nuclear Power Station was hit by the M9.1 earthquake and subsequent tsunami. The on-going project was abruptly shut down with many highly irradiated Reactor Internal components left in the Dryer Separator Pit (DSP) on the refueling floor (top floor of the Reactor Building). Some of these components are subcategorized as GTCC (Greater Than Class C) under the category of low-level radioactive waste (LLW). The LLW category is divided to Class-A, Class-B and Class-C in the order of specific activity. The subcategory of GTCC is even higher than Class-C and subject to the geological repository for disposal as with spent fuel. This means that the GTCC waste cannot be received by the JNFL’s Rokkasho facility. In the United States, the GTCC waste is loaded in the Dry Cask just like the spent fuel assemblies and stored in the designated area called Independent Spent Fuel Storage Installation (ISFSI).

There is another factor complicating the treatment of GTCC waste. When the waste is heavily contaminated with alpha nuclides above certain level of concentration, it is included in the GTCC subcategory regardless of the radiation dose rate and is scheduled for geological repository for disposal.

According to the results of the field investigation conducted by the TEPCO team after March 2019, in the “Torus Room”, the basement of Reactor Buildings of Units 2 and 3 were filled with contaminated water containing alpha nuclides at high concentration. The water volume for each unit was estimated approximately 6,000m^3. Alpha nuclides were specifically radioactive isotopes of Plutonium (Pu-238, Pu-239, Pu-240), Americium (Am-241, Am-242m, Am-243) and Curium (Cm-242, Cm-243, Cm-244). While they were mostly separated by using the 0.1-micron filter, particles smaller than 0.1 micron and ionic elements were also assumed to be contained in the collected samples.

In the case of a sample taken from Unit 2 for example, the concentration of alpha nuclides was determined to be 2.61x105Bq/L, while the concentration of all nuclides including alpha was measured 1x109Bq/L. Although this analysis result may imply that the alpha nuclides account for a very small portion, considering the high radiotoxicity of alpha nuclides, even this portion should not be overlooked.

TEPCO determined that the total inventory of radioactive materials contained in all residual water in the basement of Reactor Buildings of Units 1 to 3, Process Main Building (PMB) and High Temperature Incinerator Building (HTI) is 6.9x1014Bq. They estimate that the sludge left on the floor and exposed in air after the drainage of water would contain 1.9x1013Bq. Again, alpha nuclides make up a portion of this.

Discussions above highlight that it is important to be reminded not only when processing the residual water presently stored in the buildings. If aggressive cutting and grinding activities are performed for the fuel debris retrieval, a large TBq (Tera-Becquerel) number of alpha nuclides would be released into the air and water. Consequently, alpha-nuclide contamination would be spread throughout the Primary Containment including the Suppression Pool (Torus). This could end up with a significantly increased volume of GTCC waste which is much more problematic to handle when dismantling the plant. Also, this will increase the likelihood of decommissioning workers to inadvertently take alpha nuclides in their bodies.

As described above, the Spent Fuel Pool would not be immediately ready for draining water and dismantling even after discharging all of the spent fuel assemblies. Likewise, the Reactor Pressure Vessel and the Primary Containment (Drywell including the Pedestal and Suppression Pool – Torus) would not be immediately ready for dismantling even after declaration of completion of the fuel debris retrieval. Such retrieval work would never be perfect. The space inside of the Reactor Pressure Vessel would be chaotic with a lot of remnants of GTCC candidate components (e.g., Top Guide, Core Shroud) regardless of the presence of any residual fuel debris. The radiation level would be lethally high for the decommissioning workers. The basement floors/walls of Reactor Building and Turbine Building almost certainly covered with a film of highly radioactive sludge. Radioactive materials in ionic form or of small particles might have been absorbed on the surface of steel and concrete structures so that significant mechanical and/or chemical treatments (e.g., high pressure water jet and concrete chipping) for decontamination must be required to sufficiently reduce the dose rate. Some radioactive materials might have penetrated the basement floors / walls to the soil through minute cracks and formed a plume to migrate broadly and deeply within groundwater and along the water table.

Once again, if we review the entire program from the viewpoint of practicality and achievability and based on technical and economical feasibilities for a century-long term, is it really a wise decision to try to hastily work now with the threat of exposure to high radiation wastes and highly contaminated waste containing alpha nuclides? The harder they work, the higher the risk would be for the workers unnecessarily to be exposed to radiation and take in alpha nuclides in the body. Further additional efforts and costly measures would be required for protection or risk reduction.

Alpha nuclide species contained in the irradiated BWR fuel are as follows in the order of inventory (Bq) immediately upon the Reactor shutdown: Pu-241, Cm-242, Pu-238, Cm-244, Pu-239, Pu-240, Am-241. And the half-life of each of the top 4 nuclides is 14 years, 160 days, 87.74 years and 18.1 years respectively. These half-lives are much shorter than those species in the 5th and lower order of inventory, meaning there would be significant reductions during 50 to 100 years.

Meanwhile, it is reasonable to expect that the current technological advancement does not need to wait 100 years or even 50 years until highly advanced humanoid robots begin to play an important role in variety of industries and day-to-day lives in the human society. Having them handle high radiation zeolite sandbags and GTCC wastes with / without alpha nuclides could be one of the potential applications.

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3. Alternative Strategies

The NDF management wastefully spent too much time and resources on “Flooded Top Access” prior to 2018 when they finally gave it up. There was a serious concern about the future performance of the frozen wall. The concern became reality. The NDF team is now focusing on “Dry Lateral Access” for the fuel debris retrieval. Recognizing the fact that there is a significant difference in degree of difficulty between the pilot program whose goal is only taking some sample and the full-scale retrieval, there is a high probability that their ambitious and unrealistically optimistic plan ends up with a failure sooner or later. But even if they somehow reach the goal through exhaustive efforts, the retrieved fuel debris would find nowhere else to go from the site anyway due to Japan’s undeveloped policy and infrastructures for the ultimate disposition of spent fuel and low-level radioactive wastes. The retrieved fuel debris loaded in the storage casks must remain on stand-by on the site for a long time into the future.

After all, the intention of the original commitment “Turning to the Green Field in 40 years” publicly announced soon after the accident is becoming vague as time passes by. Since the commitment was made only for the political reason, no technical definition of the end state

Table 1: Comparison of Decommissioning Options
(Source: Author)

Option	Plan A	Fukushima Closure Plan	Plan B	Plan C
Status	Aborted by 2018	Disqualified by IRID in 2014	On-going plan developed by NDF	New Proposal
End State	Green Field	“Dry Island” isolated by moat as final disposal site	Green Field (?)	“Dry Island” isolated by moat as final disposal site
Target Schedule	40 Years	40 Years	40 Years	Indefinite
Method to Isolate Ground-water Flow	Frozen Wall + Pump	Moat	Frozen Wall + Pump	Moat + Enhanced Air / Water tightness
Method to Cool Fuel Debris	Water-Cooled	Air-Cooled	Dicision Suspended	Air-Cooled
Method of Fuel Debris Retrieval	Flooded Top Access Extendable Mast	Underground Hot Cell Extendable Mast	Dry Lateral Access Multi-Axis Arm Robot	Humanoid Robot Human Body Motion
Method to Dismantle RPV		Not Discussed	Not Discussed	Leave As-is after Decontamination (Partially Dismantled)
Dismantling PCV, Rx. Bldg.	Not Discussed	Not Discussed	Not Discussed	Leave As-is after Decontamination (Partially Dismantled)
Achievability	Extremely Difficult Uachievable	Difficult Achievable	Extremely Difficult (Unknown)	Presumably Easy
Safety / Exposure	Unacceptably Dangerous	Less Exposure	More Exposure	Minimum Exposure

was discussed and clarified at that time. One thing now clear is the reality that it does not mean achieving the 10μSv/year standard or the unrestricted unconditional release of the site as practiced for the overseas nuclear power plants in the past. Therefore, the most important thing to be done quickly by the government is to stop leaving the public under the misconception about the end state of the decommissioning. It is not a shiny "Green Field". Also, stop pretending they are marching toward that impossible goal. Then, they should redraw a new Road Map from the views of practicality and achievability based on technical and economical feasibilities. There is no 40-year time limit technically or economically.

In the previous discussions, symbolic terms "Plan A" and "Plan B" have been mentioned in conjunction with the concept of "Fukushima Closure Plan". The author believes that a better option "Plan C" is available when the 40-year time limit is abandoned. These are compared in Table 1.

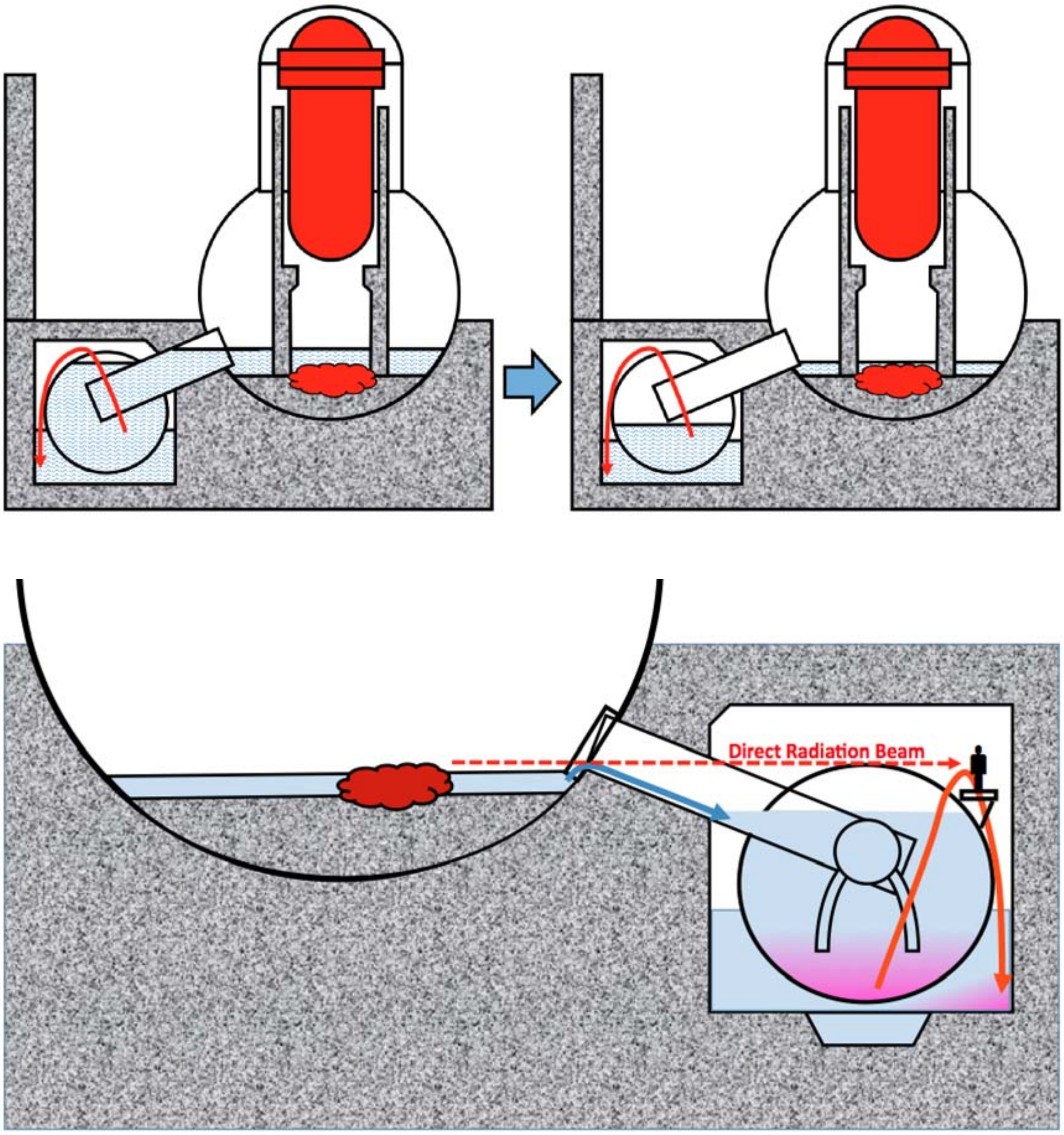
The newly proposed "Plan C" is generally based on the 2013 "Fukushima Closure Plan". However, the most significant difference between these two options is with respect to the presumed condition that all decommissioning activities must be finished within 40 years. The author reviewed the importance of this specific condition and concluded that while there is a benefit by leaving it on the table - maintaining a tense consciousness to keep the team working hard, this could exclude potential better options. But most importantly, even if this condition is escalated to the legal requirement with a strict penalty, it will not be fulfilled anyway. Spent fuel assemblies and the fuel debris loaded in the storage casks have nowhere else to go and must stay on the site. A large volume of contaminated soil must stay on the site too. The central philosophy of "Plan C" is that rather than pretending to achieve the unconditional unrestricted release within 40 years like many ordinary decommissioning plants overseas, a new realistic goal should be set for Fukushima Daiichi Nuclear Power Station, that is, converting the entire site to a permanent radioactive waste storage facility. Although this may sound like a significant step back, it will significantly enhance the efficient use of land, buildings and any other existing infrastructures as well as recyclable wastes.

Toward this new goal, the highest priority to be placed for the time being is improving confinement of the loose and vulnerable radioactive materials. Meanwhile, robot technology together with the AI technology and sensor technology is expected to make rapid progress. Once a skillful humanoid work robot, instead of the fixed multi-axis robot arm, has been developed, it would be deployed for retrieving the fuel debris. There is a lot of encouraging information suggesting this will become a key part of "Plan C".

"Plan C" is composed of the following objectives:

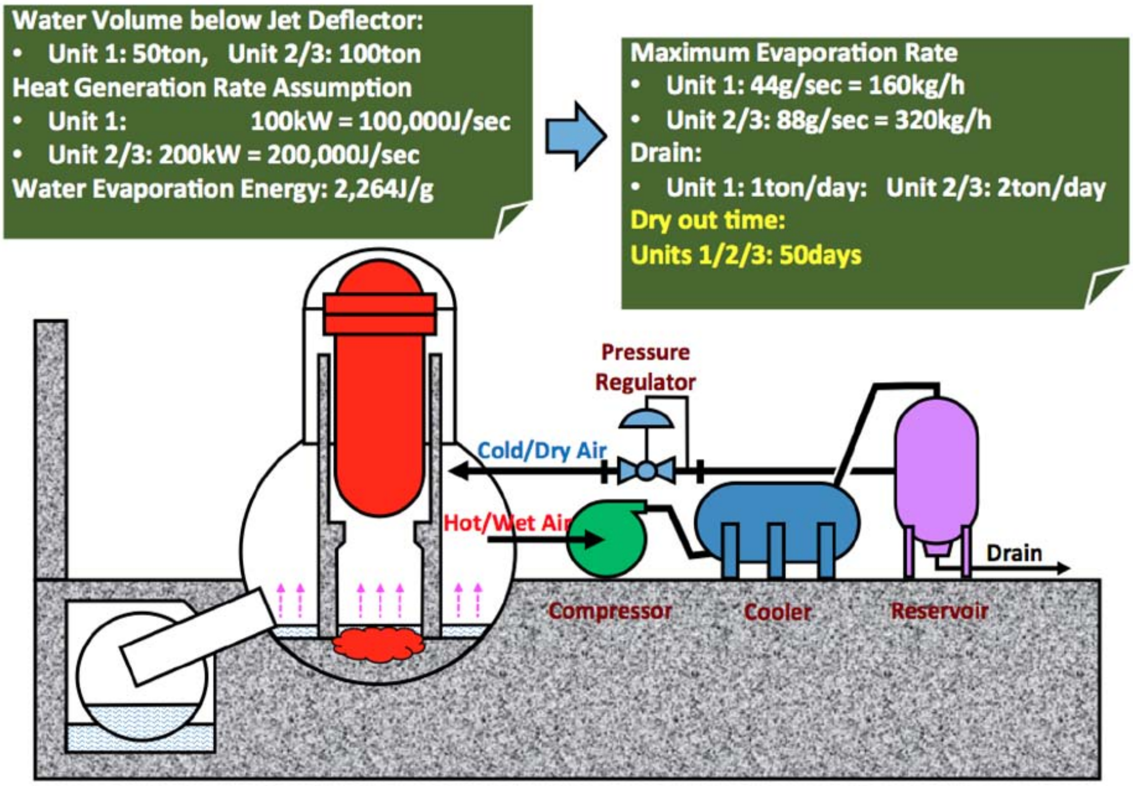
- Isolation of Groundwater: Moat
  Deactivate Frozen Wall once "Dry Island" has been developed.
- Fuel Debris Cooling: Air-Cooled Passive Design
- Confinement of Loose Radioactive Materials:
  Remove and process residual water.
  Enhance air/watertightness of Rx. Bldg.
- Storage of Radioactive Wastes:
  Near surface Trench
  Trenches become available because of lowered groundwater level after "Dry Island" has been developed.
- Fuel Debris Retrieval: Humanoid Robot
- Disposal of Existing Buildings: Reuse as Storage for Radioactive Wastes
- Security: Moat

Out of the objectives listed above, the concepts of moat and air-cooling have been described in the previous section of this report when "Fukushima Closure Plan" was discussed. These concepts are considered still valid for "Plan C" without modification. Therefore, no additional discussion is necessary in this section. One favorable change for the last 7 years is the reduction of the decay heat from the fuel debris. According to TEPCO's latest evaluation for Unit 2, it is less than 69kW. The method to remove and process the large volume of residual water contained in the Drywell and Suppression Pool (Torus) was also discussed in "Fukushima Closure Plan". The water is first drained into the Torus Room. When draining water from the Drywell, caution shall be exercised in the Torus Room because the dose level may suddenly go up significantly. And when draining water from the Torus, caution shall be exercised because the hydrogen-rich gas may be trapped in the vapor phase of the Torus. Then, the wet air is drawn from the Drywell and compressed to condense the moisture and supply the dry air back to the Drywell. The entire Primary Containment will be dried out by recirculating the system (See the sketches below).



Caution to be Exercised when Draining Residual Water from Suppression Pool (Radiation Level in Torus Room could potentially increase significantly).

Diagram 15: Drywell Drain / Dry out
(Source: Author)



Water Volume below Jet Deflector:
- **Unit 1: 50ton, Unit 2/3: 100ton**

Heat Generation Rate Assumption
- **Unit 1: 100kW = 100,000J/sec**
- **Unit 2/3: 200kW = 200,000J/sec**

Water Evaporation Energy: 2,264J/g

Maximum Evaporation Rate
- **Unit 1: 44g/sec = 160kg/h**
- **Unit 2/3: 88g/sec = 320kg/h**

Drain:
- **Unit 1: 1ton/day: Unit 2/3: 2ton/day**

Dry out time:
Units 1/2/3: 50days

Diagram 16: Concept to process Residual Water proposed in "Fukushima Closure Plan"
(Source: Author)

The author anticipates some resistance to "Plan C" for two reasons. First reason is that this plan proposes to give up the option to unrestrictedly unconditionally release the site. However, historically speaking, the original land assigned to Fukushima Nuclear Power Station later has not recently been owned by private farmers. It had in the past been land owned by the state. As of 1941 during WWII, it was the land for the Japan Army – Iwaki Airport. After WWII, it was changed to a salt farm owned by Koku do Corp. The salt business did not last long. The land, together with the adjacent forest, a total 3.2km^2, was then purchased by TEPCO at only 500 million yen. Based on this history, no one probably wishes to own any part of this land for any private reason. Letting the state land go back to the state land, or transferring the ownership of the entire asset to the JNFL would make sense.

The second reason is related to the ethical problem that people of the generation responsible for the accident will be forcing the people of future generations take their responsibility. However, it does not make any sense for the people without reliable technology to continue to waste more money for useless R&D's and ineffective actions by issuing government loan bonds to increase the national debt and force future generations to pay for them. We have the same ethical problem, but it would make better sense for the current generation to save money as a fund for the future generation to implement the actions more efficiently by using more advanced and less costly technology and methods.

The following subsections discuss the future robot technology (specifically humanoid robot), the enhancement of air/watertightness of the Reactor Building and the endurance of buildings containing radioactive materials inside.

3.1. Applications of Advanced Future Humanoid Robots

To immediately respond to the reactor accident at Chernobyl Unit 4 in 1986, approximately 4,000 soldiers were sent to the site where the plant personnel and local fire-fighters were trying to suppress the condition. They were later called "Bio-robots", meaning the human bodies that were forced to undertake a dangerous but simple operation (Scooping and throwing smoldering high radiation graphite chunks by shovels on the roof of building). At that time, even the most advanced robot in the world was not able to perform even such a simplest mission. If the modern robot technology was available at that time, a small group of robots may have saved a lot of radiation exposure for them. And if the future robot technology was then available, no one might have had to sacrifice their lives.

35 years have passed since the Chernobyl accident. Robot technology has advanced drastically along with other technological and scientific areas like material science, high density / capacity battery, AI technology and sensor technology. The humanoid robot, the same size (height and weight) as human being with no umbilical cord attached, can walk and run along difficult terrain and climb stairs on two legs. It can also open/close doors, use electric tools, operate the valve handle to open/close, do pipe-fitting and many other sophisticated tasks. Inclusions of laser/plasma welding / cutting will be as a matter of time. Operating in a team function is also a part of the capability. Those like an expandable mast proposed in "Fukushima Closure Plan" and the multi-axis robot arm proposed in NDF's "Plan B" are no longer the cutting-edge technology. 100, or even 50 years from now, the attempt to remove the hazardous fuel debris with such primitive tools must be considered possible.

The only reason why the fuel debris retrieval is such a challenging task is its extremely high radiation. Without the radiation risk, the task can be easily completed within 6 months or a year by sending many workers with the conventional hand-tools available 50 years ago and have them work around the clock. This is clearly impossible currently. Therefore, once custom-made humanoid robots who can tolerate high radiation exposure and behave like a human becomes available for the work, the productivity and safety would be drastically improved.

In the future, a team of humanoid robots would enter the Primary Containment through the X-2 Penetration instead of the small X-6 Penetration by opening the double air lock doors. They would remove any interfering structure such as steel members and grating floors on the way and proceed to their destination, the access opening on the bottom of the Pedestal. Then, they begin removing the fuel debris by using cutting/grinding tools and load the pieces into the container. The human supervisor only needs to remotely monitor their activities through cameras. If this is the future that we can expect for example in half a century or later, we should patiently wait for it while working on other things.

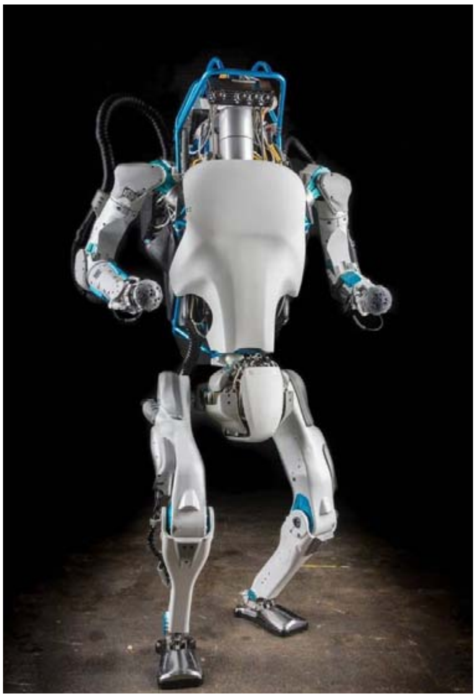


Photo 1: Boston Dynamics (ATLAS)
https://www.bostondynamics.com/atlas

3.2. Enhanced Air Tightness and Water Tightness of Reactor Buildings

While waiting for the technological advancement of the humanoid robot, the most important work to be done is the enhancement of air / watertightness of the Reactor Building so that the leakage of radioactive into the atmosphere and water and to the environment is prevented. The Reactor Building of the BWR plant is also called “Secondary Containment” as compared to the Drywell and Suppression Chamber being called “Primary Containment”. As this terminology implies, the Reactor Building is designed to be airtight consistent with the safety analysis and relied on against the postulated Design Basis Accident. However, the airtightness of the Reactor Buildings of Units 1, 3 and 4 was completely lost by the hydrogen explosion. That of Unit 2 could be also degraded due to the accident.

The watertightness of the Reactor Building was also evidently deteriorated by ageing or geologically or seismologically. When the water injected to the Reactor Pressure Vessel leaked out to the Primary Containment, it then leaked out to the Reactor Building. The Reactor Building held some water in the basement but acted only as a dam and allowed leakage through the wall and/or floor to the outside surrounded by the permeable soil which conducted the leaked water to the Turbine Building located downstream of the Reactor Building and let it spring out in the basement of the Turbine Building.

Restoration of the airtightness for the Reactor Building above the ground level is relatively easy considering the workability, inspect ability, maintenance and the magnitude of impact in case of potential leakage. The difficult part is the restoration of the watertightness below the ground level. Establishing the “Dry Island” by constructing moat entirely around the site and lowering the groundwater level would be beneficial from the point that the diffusion of the leaked radioactive materials is reduced. However, additional enhancement of watertightness for the Reactor Building below the ground level is still essential to assure the long-term integrity. There are two approaches conceivable. One working from inside and the other working from outside. Or a combination of both, to be even more effective.

The first approach, working from inside, will consist of multiple steps. As a preparatory step, apply chemical decontamination to reduce the dose rate. Then flood the basement with clean water to further improve the radiological environment for divers. Divers will apply the surface preparation and epoxy coating underwater. This procedure has been successfully applied for Spent Fuel Pools of CANDU Reactors. There are many divers trained and qualified for this type of project. The second approach, working from outside, is conceptually simple. Cladding the outer surface of the Reactor Building entirely with many sections of stainless-steel panels by welding. Applying this method underground may sound difficult. However, considering the past achievement of more difficult construction projects such as the long-distance submarine tunnels and the subway tunnels in the center of big cities as well as modern mining technology, this level of difficulty can be overcome. The author believes that both approaches above are technically feasible.

As stated previously, restoration of the airtightness for the Reactor Building above the ground level is relatively simple. The method of “Modular Construction” will be applied. Steel plates and beams are preassembled to form large panels (e.g., 15m x 15m) in the field. Their weld joints are inspected, and protective coating is applied on the ground. Then a large crane is used to assemble panels on the wall and ceiling. Each panel is welded together with adjacent panels to eventually form a large square top hat over the Reactor Building. It will be sealed to the Reactor Building with the elastic resin at just below the ground level. The panel can be considered to act as an ultimate heat dissipation for the residual heat from the fuel debris. However, since the heat to be dissipated per unit area is as small as 10W / m^2, the contribution to the surface temperature of the panel from the fuel debris is negligible.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3.3. Durability of Buildings Containing Radioactive Materials

In "Plan C", the fuel debris will be removed by the future humanoid workforce, while the Reactor Pressure Vessel, the Primary Containment and the Reactor Building will not be dismantled and instead it remains on the site after decontamination or any other treatment to prevent radioactive contamination from spreading.

Once the external surface of the Reactor Building has been entirely covered with steel panels and protected from dust, wind, acidic rain, snow/ ice and other meteorological phenomena and microscopic organisms, the deterioration of concrete and steel structures inside the building is very unlikely for a long time specially under a dehumidified dry air environment.

Radiation levels will decay, residual heat will also decay, while technology will evolve. If we trust our future, there will be more flexibility and options available to deal with this negative legacy.

4. Conclusion and Recommendations

End State

When publishing the Mid-to-Long Term Road Map, the end state as a goal should have been very so that everyone could visualize the same image.

The government and NDF should not continue to attempt to mislead as to the state of Fukushima Daiichi Nuclear Power Station in 40 years after the accident as if it would become a Green Field site. The Fukushima Daiichi Nuclear Plant is not like any other decommissioning project. The government should not pretend that they are moving toward such a goal. The following are some reasons why “Green Field” is not achievable:

- To meet the standard for the unconditional “Green Field” release, the radiation dose rate everywhere in the site should be less than 40 or 10μSv/year if the U.S. or U.K. standard is applied respectively. A large volume (as much as nearly 10 million m^3) of contaminated soil must be removed from the site for disposal. This is an extremely difficult work to do, and there is no place to remove the waste to outside the site.
- There will be more than ten large storage buildings remaining on the site for radioactive waste even after the volume reduction by incineration and other processes. Because of the volume, they will remain on site. It should be noted that this estimated volume does not include the amount of radioactive waste to be generated when Units 1 to 6 are physically dismantled.
- If Units 1 to 6 are entirely dismantled, an additional 1.5 to 2 million tons of concrete debris and steel scraps will be generated. There is no place available in Japan to where this material could be moved.
- Many dry casks and shielded containers containing spent fuel assemblies, highly irradiated Reactor Internal components, depleted control rods and channel boxes, and secondary wastes generated by processing the contaminated waste are left on the site and must stay until the final disposal strategy has been determined and the facility for disposal has been put into service. When the fuel debris is retrieved from Units 1 to 3, their storage casks must stay on the site.

The government and NDF should not attempt to justify wasting resources based on an unrealistic assumption that turning Fukushima Daiichi Nuclear Power Station to the “Green Field” is the sole and best solution. The most realistic option for the future usage of the land of Fukushima Daiichi Nuclear Power Station will be, whether welcomed or unwelcomed, a facility for the long-term storage of radioactive waste. All of the problems listed above are automatically resolved by accepting this reality.

Fuel Debris Retrieval by “Dry Lateral Access”

Just taking small samples of the fuel debris from the Pedestal as a pilot demonstration at Unit 2 by using a multi-axis robot arm designed to access through the X-6 Penetration will be achievable. However, once it is escalated to the full-scale production by expanding the X-6 Penetration, the level of difficulty will be exponentially increased. The retrieval will be narrowly limited within the accessible range while residues inside the Reactor Pressure Vessel will be left undone. After all, unless changing to a different method (more flexible and accessible, more efficient and productive method), the fuel debris retrieval will not be accomplished. When the fuel debris retrieval is attempted by drilling, cutting or grinding underwater, highly concentrated contaminated water containing alpha nuclides will be generated. When it is attempted in dry environment, the entire space inside the Primary Containment may be contaminated with alpha nuclides. Some effective provision against these waterborne or airborne problem needs to be developed and provided for mitigation.

Even if the pilot demonstration has been successfully accomplished, the information gained from the results is limited and incomplete with respect to the property of fuel debris. Therefore, the information will not be valuable to proceed to the next stage. The planed application of “Dry Lateral Access” by using the robot arm should be limited to this demonstration and the application for the full-scale production should not be pursued.

Cooling Method for Fuel Debris and Resolution for Contaminated Water

As long as water is used to cool the fuel debris, radioactive materials leach out and the production of contaminated water will not end. As long as the isolation of groundwater leaking into the Reactor Building and the Turbine Building depends on the flawed frozen wall, the leakage into the buildings will not end. The accumulated volume of contaminated water will continue to increase and with the daily fluctuation of rainfall. To permanently terminate these situations, it is proposed to change the way to cool the fuel debris from water-cooling to air-cooling and to replace the frozen wall with the moat concept.

The moat will isolate the flow of groundwater originating from Abukuma Heights. The groundwater level in the site, once isolated from the water source, will drop eventually down to the seawater level. The groundwater leaking into the Reactor Building and Turbine Building will be drastically reduced.

Plan C

The decommissioning program should not treat each objective (1- reducing contaminated water production, 2- fuel debris cooling and 3- fuel debris retrieval) independently. Since they are all interrelated, they should be treated as a single package. The decommissioning program should be developed to be consistent with what the end state of the site is supposed to be. The alternative decommissioning program proposed in this report is called “Plan C”. “Plan C” is composed of the following objectives:

- Isolation of Groundwater: Moat
  Deactivate Frozen Wall once “Dry Island” has been developed.
- Fuel Debris Cooling: Air-Cooled
  Passive Design
- Confinement of Loose Radioactive Materials:
  Remove and process residual water.
  Enhance air / watertightness of Rx. Bldg.
- Storage and Disposal of Radioactive Wastes: Trench
  Deep trenches become available because of lowered groundwater level after “Dry Island” has been developed.
- Fuel Debris Retrieval: Humanoid Robot
- Disposal of Existing Buildings: Reuse as Storage for Radioactive Wastes
- Security: Moat

The moat is a passive system requiring no external power to function. Therefore, the only in-service maintenance required periodically is dredging mud and sand that may be carried into the system by rainfall and seawater. Once the moat has been completed, the site becomes an isolated island with its groundwater level dropped as low as seawater level and provides various optional usages and beneficial features. A large deep trench as a storage / disposal facility for radioactive waste is an optional useful application. Diffusion of radioactive materials being deactivated within the dry soil is advantageous for this application. Likewise, the fuel debris cooling by air can be designed as a passive and maintenance-free system requiring no external power to function. It only relies on the natural thermal conduction, convection and radiation to dissipate the residual heat of the fuel debris.

For further information

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