# A Liquidation Strategy of Fukushima Daiichi Nuclear Power Plant: A new "In-Situ Entombment Plan" proposed

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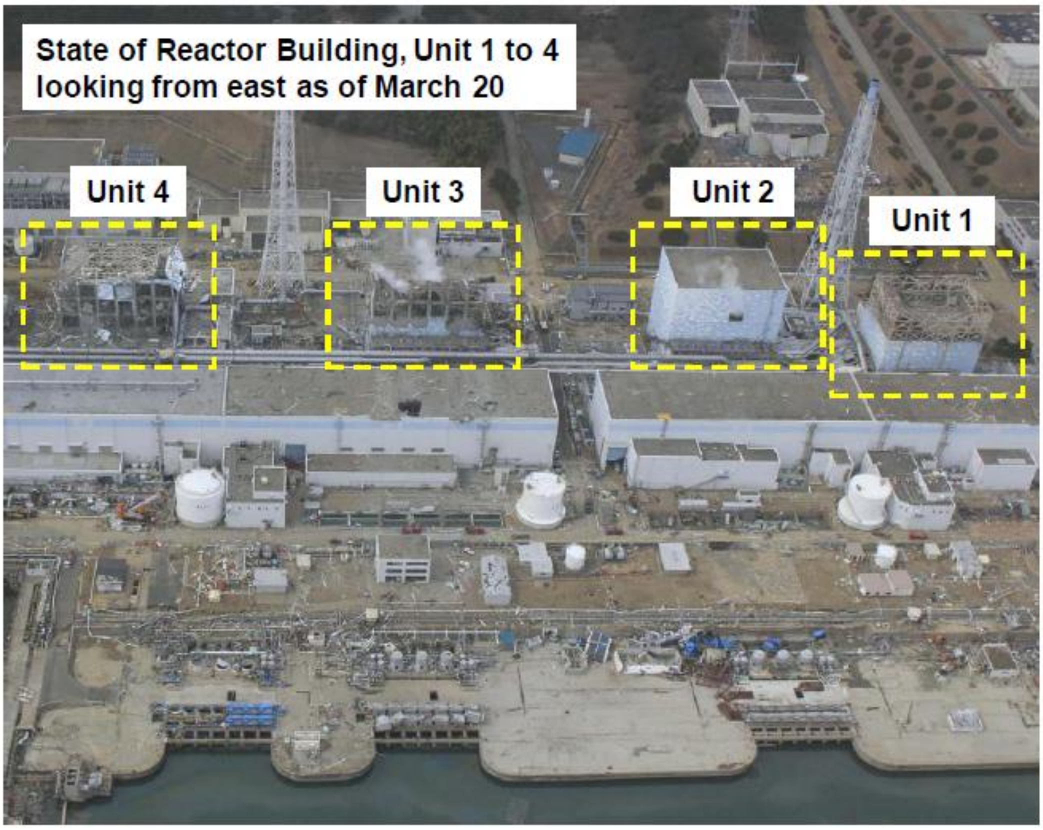
**Abstract**

I studied the Green Field Plan, currently on-going in Fukushima Daiichi Nuclear Power Plant aiming at decommissioning of the Fukushima Daiichi area to "Green Field", and found that it is practically impossible if taking into account of the situation of the nuclear reactors and the urgent matter preventing air and ocean pollutions. Instead, I propose "In-Situ Entombment" Plan, characterized by (1) a flexible and doable liquidation strategy to abandon Fukushima Power Station, (2) water treatment and entombment, (3) on-site above ground repository to design beyond millennium, and (4) concrete technological proposals how to stop pollutions in air and ocean along the realistic time table.



# Executive Summary

## 1. Present Status of the nuclear plant

Based on publically available information, I concluded the followings (Table 1 and Figures 1 and 2):

1) The reactors of Units 1, 2 and 3 were all severely damaged: Reactor core (1,2) is totally destroyed by the complete loss of cooling capability over the six hours (14h 09m for Unit 1, 06h29m for Unit 2, and 06h43m for Unit 3). Most of the fuel rods broke down to the core plate and considerable fraction of them penetrated into the bottom head of the primary containment (Figure 1). Some of them possibly still penetrated down to the floor to start concrete interaction at the floor (Figure 2), although they, most likely, do not penetrate the floor concrete, thanks to the water injection operations. Since water tightness was lost in the reactor pressure vessels totally and in the primary containments partially, the injection of considerable amount of water is necessary to keep the level of water in the reactors. Only Unit 4 is in a healthy condition, since it was fortunately empty on March 11.
2) There are no conclusive information so far on Spent Fuel Pools (SFPs) and the fuel rods inside them. SFPs of Units 3 and 4 are suffered from potential thermal damage due to overheating and those of Units 1 and 4 are from potential mechanical damages due to the earthquake and/or the hydrogen explosions. Spent fuel rods in Unit 2 look undamaged.
3) The buildings of Units 1, 3, 4 were all severely damaged by the hydrogen explosions. The peripheral instruments such as an overhead crane are not usable.

Table 1: Summary of Fukushima Daiichi Nuclear Power Plant

| Unit | Reactor Core | Reactor Pressure Vessel | Primary Containment | Reactor Building |
|---|---|---|---|---|
| 1 | Totally destroyed | Barrier integrity no longer maintained. Bottom Head Penetrations severely damaged. | Barrier integrity no longer maintained. Details not confirmed. | Original Function as Secondary Containment totally lost due to H2 explosion on Refueling Floor. Remaining part of building still reasonably good. Overhead Crane (OHC) and Fuel Handling Machine (FHM) not available. |
| 2 | Ditto | Ditto | Barrier integrity severely degraded due to H2 explosion inside or outside Torus. | Function as Secondary Containment still reasonably maintained even after H2 explosion. OHC and FHM still fully functioning. |
| 3 | Ditto | Ditto | Same as Unit 1 | Same as Unit 1, except that some portions lower than Refueling Floor also degraded due to H2 explosion |
| 4 | Empty | Not affected | Not affected | Ditto |

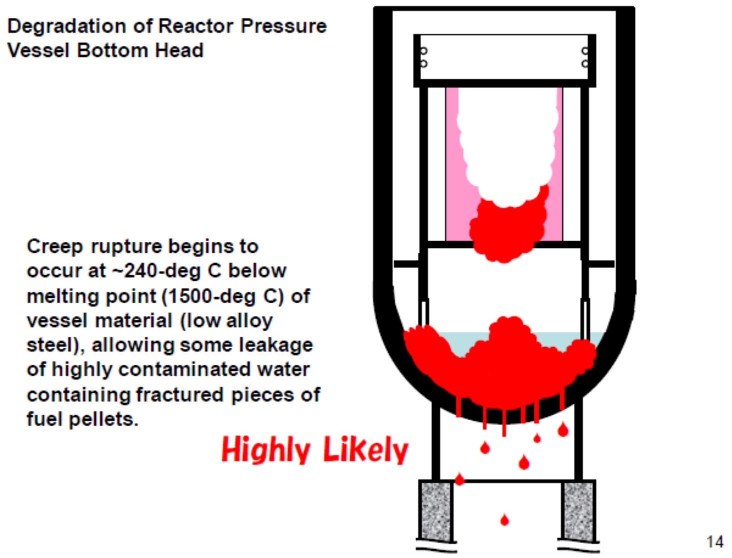



Figure 1. Degradation of Reactor Pressure Vessel is Highly Likely.

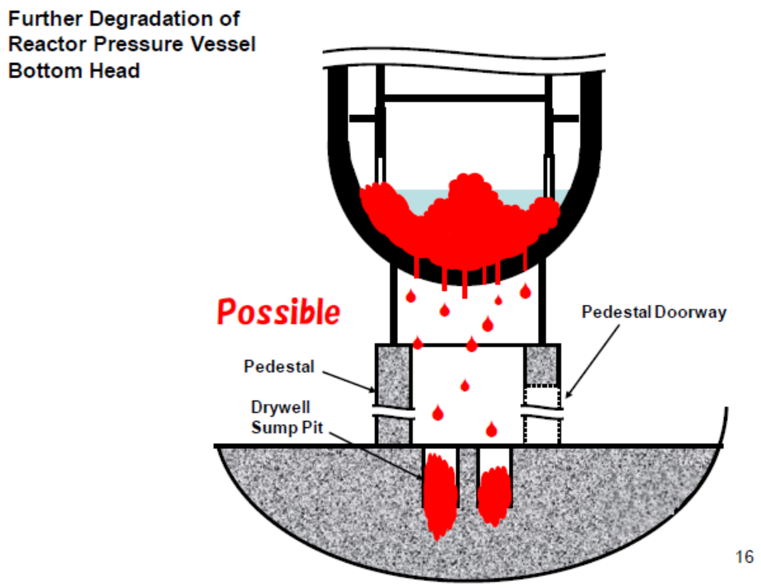



Figure 2: Possibly Further degradation happens.

## 2. Green Field Plan (4,5,6): too many difficulties in decommissioning to "Green Field"

The currently on-going actions based on TEPCO's long term plan of decommissioning of Fukushima Daiichi NPP are shown in Table 2. It seems to aim the "Green Field", though the final stage is not clearly stated in their plan. However, based on the recognition of the present situation described above. I concluded that the decommissioning of the Fukushima Daiichi area to "Green Field" is impossible, because of the following reasons.

Table 2: Long term decommissioning plan of Fukushima Daiichi NPP by TEPCO

New timetable for trouble-shooting of nuclear accident of TEPCO (major amendament)

| schedule | | April 17 | Step 1 (finished by the end of July) | Step 2 (from mid-Oct. 2011 to Jan. 2012 ) | mid-term purpose |
|---|---|---|---|---|---|
| coooling | nuclear reactor | input of fresh water; minimum; preparation; repair of | watering (water cooling); for reuse of polluted water; broken part of container; working cond. enhance.; circulat; establish. heat exchange system; Stable cooling | water cooling; complete drowing of container; Cold shutdown | stop corrosion of reactor and pipes |
| | fuel rod pool | | remote control of watering; setting heat exchanger | more stable cooling | extraction fuel rod |
| control | polluted water | transport. polluted water | stop ocean pollution; storage | lowering amount; stop ocean | completion of polluted water treatment; pollution |
| | underground water | | stop underground | water pollution | build. barrier for underground water |
| prep. for after shock | tsunami/ shake | protection | for aftershocks and tsunamis; reinforment; prep. multiple radiation barrier | of each reactor | reinforment of each reactor |
| environ. enhance. | life/work environ. | | enhancement of working | conditions | |

- The recovery of the fuel rods in the reactors in Units 1, 2, and 3 is absolutely impossible, because of the damages of the rods themselves and the loss of the peripheral instruments such as cranes, by the hydrogen explosions.
- The injection of water to the vessels must be reduced, since it produces prohibitally large amount of heavily-contaminated waters to leak down to the ground and underground of the nuclear power plant. It will flow out to the sea according to the flow of the underground water.
- Building, soil, and groundwater around the site are widely and severely contaminated by radioactive isotopes, including Plutonium.
- No candidate repository locations available for a large volume of heavily contaminated materials and concrete rubble.

## 3. "In-Situ Entombment" Plan: Realistic alternative approach to "Entombment"

I recommend an alternative approach to achieve effective "Entombment" of the

Fukushima Daiichi Field by the following procedure, outlined as follows:

- Gas/Air cooling system by forced circulation at first and then natural circulation at the end.
- Remedy for leaky system: Introduce fine glass fiber mixed with SiC/$B_4C$ powder to clog leaking paths and then use chemicals to introduce precipitants, such as $Ca_3(PO_4)_2$.
- Heavily contaminated water, currently stored in the pools or the containers, can be mixed with contaminated concrete rubble to make ready-mixed concrete to use for entombment works, if their radiation level become lower than 5,000 Bq/cm$^3$ after treatments. Concentrated radioactive liquid will be stored in onsite depository after vitrificated in appropriate containers.
- Building of the concrete shield made down to 20-30m (TBC) underground to avoid inflow of underground water to confine heavily contaminated water leaked down to the underground of the nuclear plan buildings.
- Minimize $^{131}$I airborne inside and outside of the reactor buildings by spraying TSP (Trisodium Phospharate: $Na_3PO_4$) solution.

## 3.1. Cooling of the Reactors

According to the decrease in heat release, the way of the cooling the reactors will be changed as follows:

- Mode 1: Helium cooling with forced circulation (Figure 3)

Helium gas is injected through *A* (figure 3) by ventilation system into the reactor core. The metal structures in the core work as heat sinks to transfer heat to helium gas effectively. The cooled gas is introduced to the suppression chamber to evaporate water there. The heated gas with water vapor is collected by the ventilation pipe, which is newly installed at the top of the reactor container. The helium gas, which is removed the contaminants at the Scrubber/Gas cooler, is circulated again. The containment of the gas is examined to study the status inside the reactors. The space between the reactor pressure vessel and the primary containment is filled by mixture of gravels such as copper sphere shells, zeolite, and perlite taking into account of high thermal conductivity, radiation shielding, and absorption radioactive gas/particles (Figure 4).

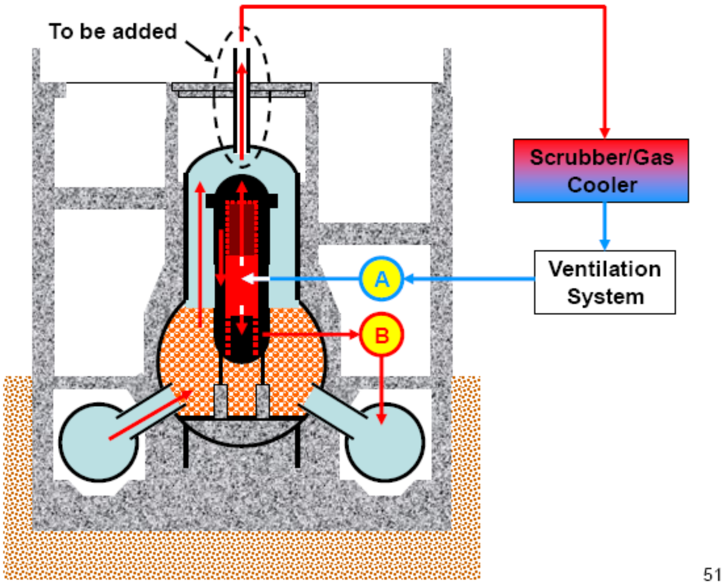



Figure 3: Helium cooling with forced circulation (Mode 1)

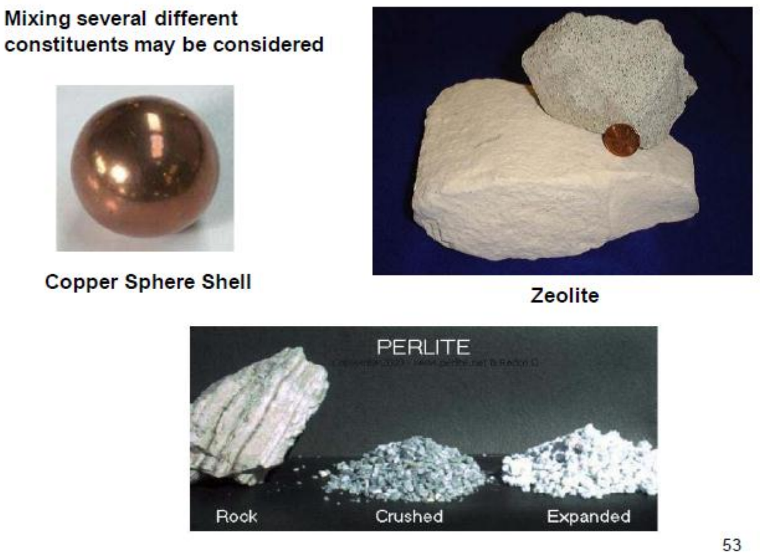



Figure 4: The primary containment is filled by mixture of gravels such as copper sphere shell, zeolite, and perlite taking into account of high thermal conductivity, radiation shielding, and absorption radioactive gas/particles

- Mode 2: Air cooling with forced circulation (Figure 5)

Air is injected to the suppression chamber by ventilation system through newly installed pipes. The air circulates the space between the reactor pressure vessel and the primary containment to cool down the reactor vessel from the outside. The air is extracted through the pipe at the top the reactor.

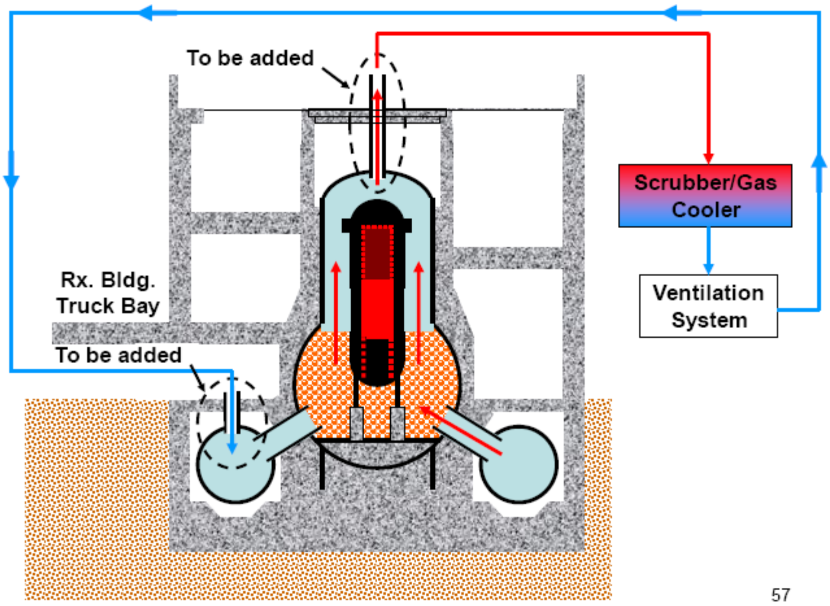



Figure 5: Air cooling with forced circulation (Mode 2)

- Mode 3: Air cooling with natural circulation

Air actively extracted from the top of the reactor. New air naturally gets into the pipes at the suppression chamber and other leaking place (Figure 6). In later phase, the pipe at the top of the reactor pressure vessel may be filled-out or removed. The air is naturally circulated just outside of the primary containment and extracted through the stack (figure 7).

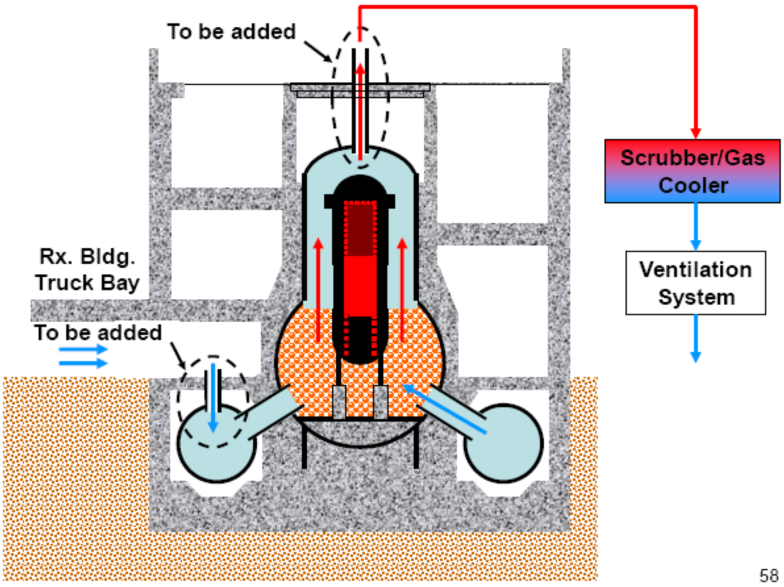



Figure 6; Air cooling with natural circulation (Mode 3)

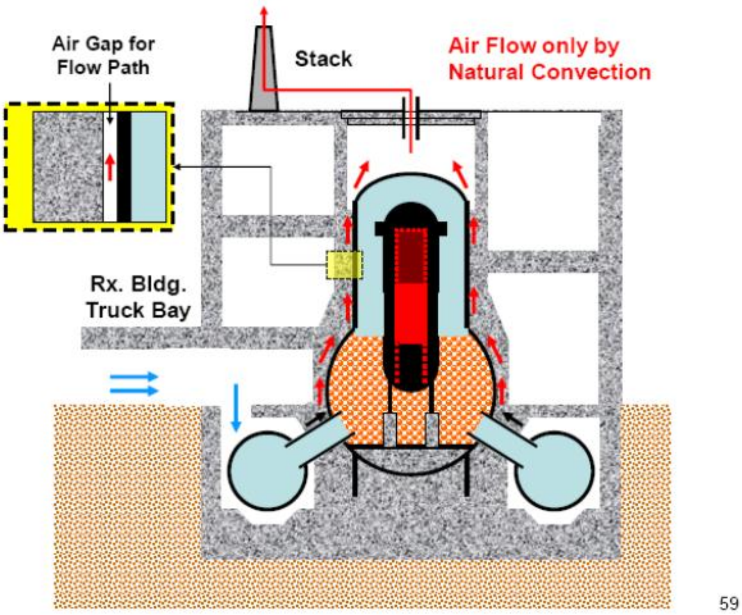



Figure 8: Natural cooling by the air at the end

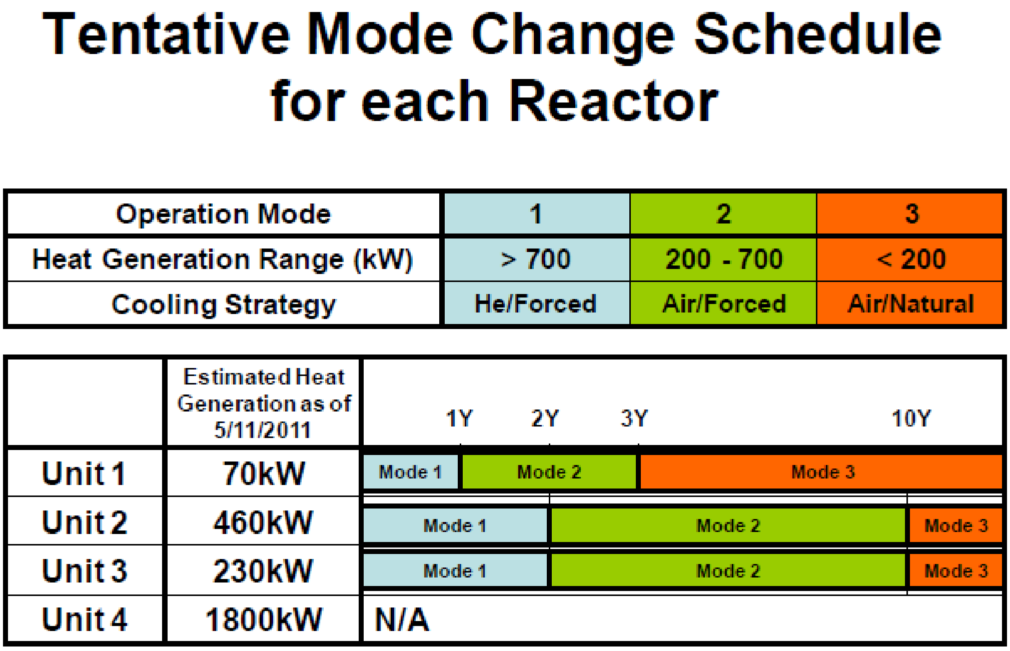



Figure 8: Time schedule of the Reactor in "In-Situ Entombment" Plan

3.2. Cooling of the Spent Fuel Pools

The fuel rods in the spent fuel pools of Units 1, 3, and 4 are also cooled down using newly installed metal chambers with a finned heat sink as well as a mixture of gravels, such as used in the reactors. They are cooled by water at first then gradually replaced by air with a carefully designed circulation systems. The fuel in the Unit 2 may be extracted to transport to the Rokkasho Village, Aomori Prefecture, spent fuel facility after careful inspections.

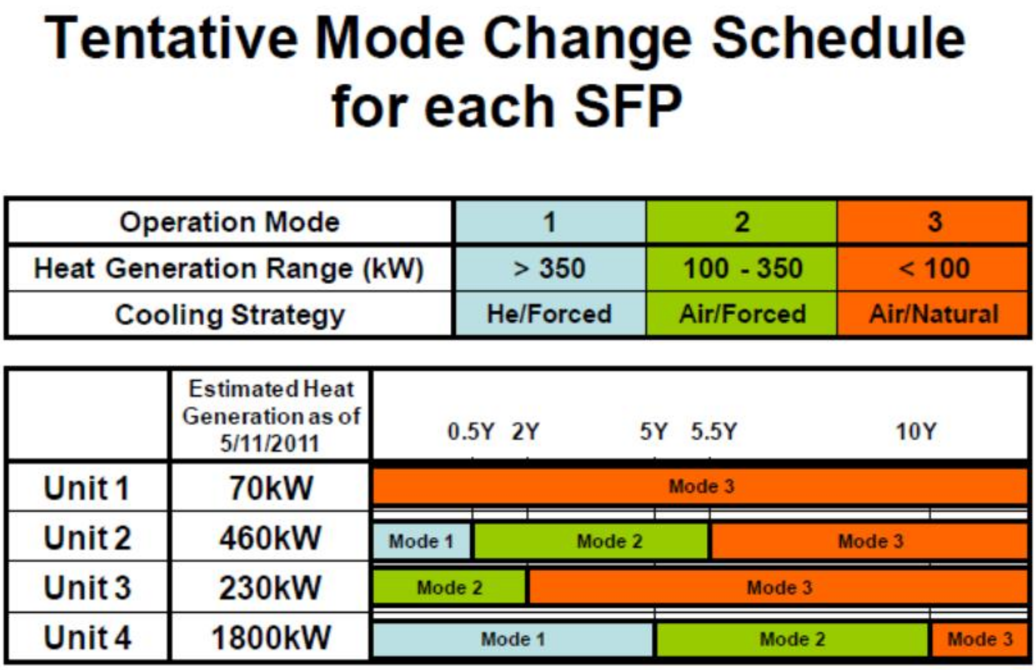



Figure 9: Time Schedule of Spent Fuel Pool in "In-Situ Entombment" Plan

### 4. Worst case; a new proposal to bury whole building systems

In the worst case, *e.g.*, the melt U-oxides had already been beneath the concrete basement of the building, and dropping further down into the Tertiary half-consolidated sandstones. As the wall-rock sandstones melted to mix "U-Zr oxide magma", the temperature of the magma cools. Depending on the size of initial U-oxide with melted Zr oxide, the magma will finally consolidate and stop at the depth of around 10-20 m. The surrounding sandstone would dehydrate to release water-rich fluid to move upward together with contaminated radionuclides. To prevent air pollution by these fluids rising upwards, mixtures of clays, pumice with zeolites, graphite, and organic matters are set in the space above the reactors and building. On the top of the shielding roof, a chimney is built including numbers of filters in it to absorb radionuclides.

If this process had happened already or may occur in future, the extensive chemical pollution may continue, because the underground water derived from surrounding regions on-land transports the radionuclides to the Pacific Ocean. To avoid the pollution, a thick wall of concrete must be made surrounding the entire region of all of six power stations up to the deep about 20-30 meters (Fig. 10). These walls also stop the leaked contaminated water to spread out to the environment.

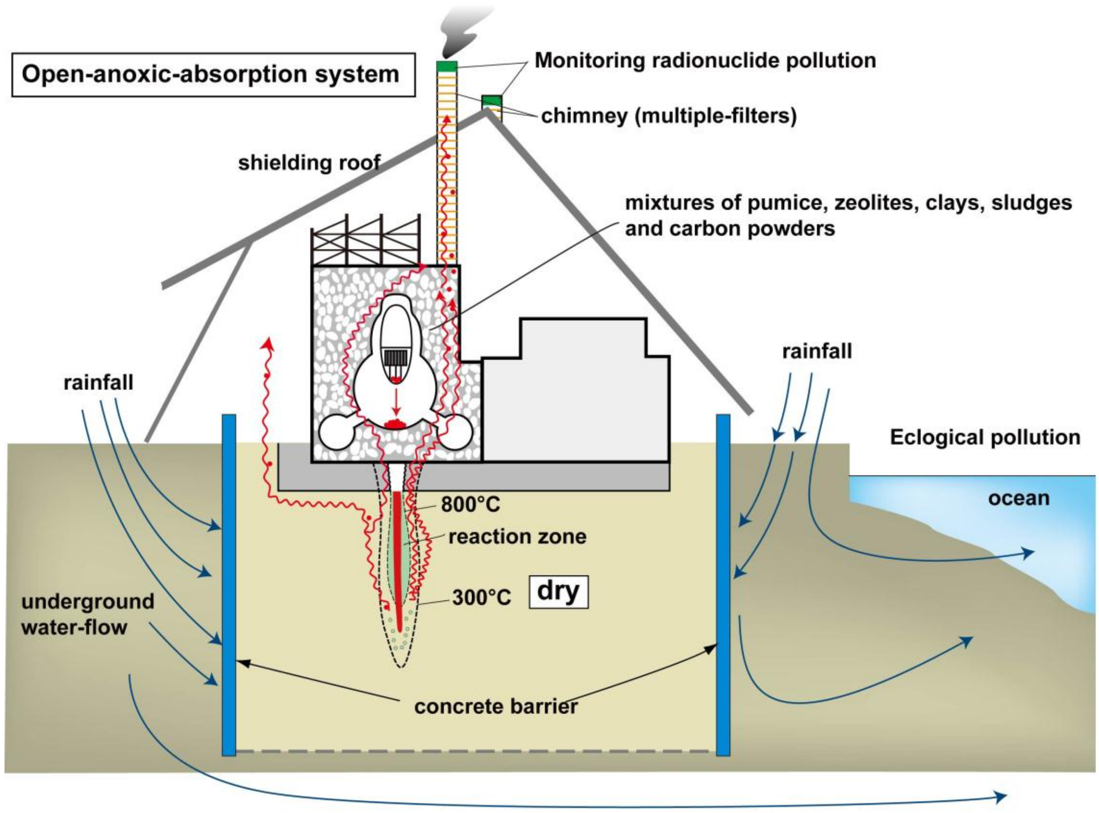



Fig. 10 A plan to bury the entire building system by 1)open system to escape vapors through a chimney on the top, 2) oxygen-free system to prevent from explosion by hydrogen using the carbon powders, anoxic and organic matters enriched sediments (sludges), pumices (zeolite) and clays, and 3) absorption of radionuclides by the enclosed materials such as zeolite, clay and graphite. Multi-layered filters in the chimney would work to clean-up the polluted fluids at final stage on the top of chimney to monitor the amounts.

## 5. Beyond "Entombment"

New infrastructure or facilities with cutting-edge technologies is necessary to economic recovery of the heavily damaged area around the Fukushima Daiichi NPP. Those could be

- Infrastructure powered by solar power with newly introduced technologies
- Research facilities for the remediation of the environment by naturally available resources and radiation biology.

## References

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## Epilogue

On March 19, 2011, SS released the first brief technical report that the reactors of Units 1, 2, and 3 in Fukushima Daiichi Nuclear Power Plant had melted down because of the complete loss of the cooling capability over six hours. More comprehensive technical report was released by International Access Corporation on March 28, 2011. SS gave a lecture titled “Nuclear Disaster at Fukushima Daiichi NPP: Current Status and Anticipated Issues about Recovery Project” at RIKEN on April 22, 2011. Meanwhile, TEPCO continued to argue that the damages in the cores of the reactors and spent fuel pool in Fukushima Daiichi NPP were not serious. However, they suddenly released that the core of the Unit 1 was seriously damaged and probably melted down at least partially on May 12, and furthermore on May 24, they reported that cores of Unit 2 and Unit 4 were also melted down.