Chapter 5

Experiences from the Fukushima Disaster

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Additional information is available at the end of the chapter

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Abstract

The nuclear accident of the Fukushima Daiichi reactors on March 11, 2011, could have been prevented if the owner and the responsible Japanese ministries had considered the worst-case scenario when planning the reactors near the coast, including at least double redundancy of the emergency system. After the exceptionally strong earthquake, the reactors correctly switched off. The problem started due to the tsunami that destroyed the emergency generators, which should have driven the cooling pumps after the reactor-power had switched off. The Zr-alloy mantles of the fuel rods reacted at the high temperature with water to form ZrO_2 and hydrogen. The following explosions, destruction of the reactor buildings and meltdown caused large radioactive clouds and the evacuation of 150,000 people. This chapter shows how by immediate efforts most of this cloud could have been sucked off. The radioactive soil from large contaminated areas was later collected in plastic sacks. Continuous cooling led to huge amounts of contaminated water that was collected in large tanks. In future, the reactor has to be dismantled resulting in contaminated debris. In this chapter, the possible solutions of radioactive cloud, soil, water and rubble problems and the final deposit of used fuel rods are discussed. The experiences could become useful in case of a future nuclear accident.

Keywords: Fukushima accident, tsunami risk, radioactive cloud, contaminated soil and water, reactor dismantling, nuclear risk, energy future

1. Introduction

With increasing world population, with increasing industrialization of less-developed countries and with increasing electric mobility, the demand of nuclear energy will increase. When renewable energy from the wind and the sun increases worldwide, from the present 0.8%, then nuclear energy will be needed as base energy to compensate the lack of electric energy when the wind is not blowing and the sun not shining. Furthermore, with the limited world resources of coal and oil, and with the required reduction of CO_2 emission with regard to the climate problem, the role of nuclear energy will increase in most industrialized countries. Accordingly, nuclear reactors are being built or are planned to be built in most countries except Germany and Switzerland where, by emotional decisions taken after the Fukushima accident, nuclear energy is planned to be terminated. These two countries could then be faced with lack of reliable electric power supply and with the increasing cost of electricity from 30 to 50%, a risk for industries and for the expected electric mobility. Their choice will be the import of nuclear energy from neighbor countries (with increasing risks of radioactive clouds in case of future accidents) or the installation of gas-power plants with dependence on gas supply and with emission of CO_2. Energy policies should be discussed in view of sustainable management of limited energy sources [1] until in the far future nuclear fusion energy may hopefully be developed [2].

Most of the present 450 plus nuclear reactors are of type II Pressurized Light-Water-Moderated and Cooled Reactors. The energy efficiency of the uran-235-based fuel rods is only 1.5–5%. Their recycling yields plutonium needed for nuclear bombs, the reason why this reactor type was pushed by the US military. On the other hand, can the later recovery of used fuel rods from the storage site of radioactive waste become a significant source of energy for future generations? Now 60 reactors of higher energy efficiency are being built or are planned on being built, with the example of the European Pressure-Water Reactor being built in Finland.

The risk for life and health of the nuclear energy is much smaller than the risks of fossil energy and of renewable energy taking into account the direct fatalities and the after-effects from air pollution from burning fossil fuel [3] and from the role of CO_2 for climate change. The new generation of safe type III and type IV generators including thorium reactors will have high energy efficiency, cause significantly less radioactive waste and shorten the required storage time for radioactive waste [4]. Until these modern reactors are fully developed, mankind should learn from experiences of the two nuclear accidents in Chernobyl and Fukushima with respect to optimized planning of the safe site of the reactor including its safety infrastructure, considering the worst-case scenario of all possible risks. The following discussion of the Fukushima problems may help in case one of the existing nuclear reactors should have an accident although the probability is extremely small. After the Fukushima incident, the existing nuclear reactors in Japan should be checked with respect to the worst-case scenario of earthquake and flooding risks. Also, the risks of extremely complex technologies should be considered. One could discuss whether all reactors worldwide should be checked by an international specialist team, possibly under guidance from the International Atomic Energy Agency (IAEA) in Vienna taking into account the national nuclear safety organizations.

2. Critical planning phase of the Fukushima Daiichi plant

The start of a nuclear power plant requires the study of all potential risks like earthquakes, landslides, aviation routes, the risks of flooding from mountain sides and from seaside and extreme weather. Also, the groundwater situation has to be considered. The primary responsibility is with the owner of the plant and its planning team. The government and its ministries have the main control function, and the International Atomic Energy Agency (IAEA) in Vienna has the obligation to supervise the safety aspects especially in view of preventing proliferation of nuclear material.

In case of the Fukushima Daiichi plant, the owner company did not consider the worst-case scenario for financial reasons [5]: Despite the in-house study which revealed the possibility of 10 m high tsunami waves, the company's headquarters declared such a risk as unrealistic. Also, warnings from the Research Institute of Earthquake and Volcano Geology of the Geological Survey of Japan and of the US Nuclear Regulatory Commission were not followed by the company and by the responsible safety agency of Japan. This agency had a conflict of interest and was replaced in September 2012 by the Nuclear Regulation Authority under the Ministry of the Environment [6].

In order to protect the Fukushima coast against tsunami with the miss-judged low heights of the waves, seawalls of about 10 m height were erected, see **Figure 1**. This photo was taken after the accident and also shows the tanks with radioactive contaminated water. The north seawall shows the remaining low height (probably caused by the tsunami) and the two seawalls of the remaining height of claimed 10 m.

The plant owner failed to arrange safe electric backup generators and a reliable emergency cooling system which resulted in the primary cause of the Fukushima accident.

Earthquakes above magnitude 7.0 were of concern for the IAEA due to large earthquakes earlier. However, the March 11, 2011, earthquake with magnitude 9 did not damage the Fukushima plant [5], it caused the correct shutdown of all reactors.

Figure 1. Top view of Fukushima power plant Dezember 2015 with lateral and height dimensions.

The failures of the planning phase and the actual causes and sequences of the Fukushima disaster have been analyzed by an independent commission which was appointed by the Japanese Government and which delivered the report July 5, 2012. The conclusion was that the accident could have been prevented and that it was man-made. Furthermore, the evacuation conditions were criticized as they caused 1600 fatalities due to stress from the hectic exaggerated evacuation, whereas radiation did not cause direct death [5].

The Fukushima accident has demonstrated the interaction of neighbor reactors: the meltdown problem of reactor 1 effected meltdown and hydrogen explosions in reactors 3 and 4. As consequence, a minimum distance between reactors of say 50 m should be demanded in future and all reactors provided with individual emergency power supplies, pumps and other safety equipment. In existing rows of reactors, they should be separated, for instance, by steel plates and have individual safety equipment, all with at least three-fold redundancy.

3. Effects of the March 11, 2011, earthquake and tsunami

Japan is situated on the Pacific Ring of Fire with active plate tectonics where the Pacific Plate is subducting the Eurasian Plate and thus causes frequent earthquakes. The country has spent remarkable efforts to reduce the risks of collapsing buildings. When earthquakes of magnitude larger than 6.5 occur in the sea, they may cause tsunami depending on the displacement of the seafloor actually caused [7]. Such tsunami can lead to flooding on the coast and cause numerous fatalities: in case of the 2011 tsunami, 19,000 fatalities and large damages. However, such tsunami catastrophes are not so frequent so that protection measures have been realized only in a few areas. Frequently, classical breakwaters are constructed by placing heavy caissons onto rubble mounts or foundations which have a slope on the seaside [8]. The typical failures of such breakwaters consist of sliding or tilting of the caissons [9]. One example is the harbor city Kamaishi north of Sendai at the Honshu/Japan coast where, after experiencing the 1896 tsunami catastrophe, the world's largest breakwater was built in 31 years at the cost of 1.3 billion US dollar. Only 6 months after celebrating the world record for Guinness Book of Records, the Tohoku tsunami of March 11, 2011, destroyed most of the breakwater and part of the Kamaishi harbor region and caused 1000 fatalities. Details of the construction of the combined breakwater and of the damages have been described [10]. Recently it was shown that this breakwater had been built on the wrong site with a non-optimal technology [11] and that a submerged barrier, with vertical wall toward the sea, at the entrance of Kamaishi bay would have prevented the local tsunami catastrophe.

The tsunami pressure (impulse) waves travel from the earthquake area at a high speed of typically 700 km/hour at an ocean depth of 4 km in all directions. The velocity c is given by

$$c = \sqrt{(g \times h)} \tag{1}$$

with g the gravitational acceleration and h the water depth. By the law of energy conservation, the kinetic energy of the pressure waves is transformed to potential energy when the wave approaches the coast with decreasing water depth according to

$$A^2 \times c = \text{constant} \tag{2}$$

where, A is the amplitude or wave height. With a starting wave height between 0.3 and 1 m in the deep sea, the wave height will increase at the coast to 3 and 10 m and can rise in narrowing bays to values up to 38 m as observed 2011 with the Tohoku tsunami [11]. As a consequence, the seaside of submerged buildings in the sea should not have slopes, should always be vertical walls.

In order to prevent the tsunami flooding catastrophes, the concept of a submerged vertical barrier (wall) has been developed which reflects the tsunami impulse waves and also the storm surges from a typhoon so that these Tsunami-Flooding-Barriers (TFB) would have prevented the Fukushima disaster [11].

In the case of the Fukushima plant, three classical breakwaters (seawalls) have been built as shown in **Figure 2**.

The northern breakwater in the Google photo, taken after the accident, shows a low height and flat surface indicating that the caissons on top of the rubble mound foundations may have slit down. The western and southern breakwaters showed a height between 10 m and 13 m and thus were still intact.

The tsunami pressure wave, which arrived from the north-eastern direction, is indicated in **Figure 2** by the red arrow. The wave height was increased at the slope of the northern breakwater. Then the tsunami energy was focused by the two remaining breakwaters toward south-west explaining that the southern Reactor 1 with its emergency auxiliary equipment was damaged, whereas the northern reactors 5 and 6 were not affected from the tsunami.

The height of the tsunami water front was estimated as 13—15 m, but in view of the concentration effect, it may have been locally significantly higher when approaching the southern reactors 1– 4 and their emergency equipment.

The following description of events is a concentrated summary of reports detailed in [5].

From the six reactors, the units 4–6 had been shut down for a normal-scheduled inspection. The reactors 1–3 had been operating and were immediately switched off when the earthquake struck. Therefore, the reactors did not produce electricity and could not use their own power. The available emergency diesel generators were disabled from the floods; also, the switching stations for the diesel generators at higher position were flooded. Furthermore, the attempts to connect the water pumps to portable generators failed. Due to lack of sufficient cooling, the fuel rods with zircaloy mantle reached temperatures above 1000°C where the exothermic reaction $Zr + 2\ H_2O >> ZrO_2 + 2H_2$ produced explosive hydrogen. This then caused in the following days successive explosions in reactors 1, 3 and 4 destroying the roofs and tops of

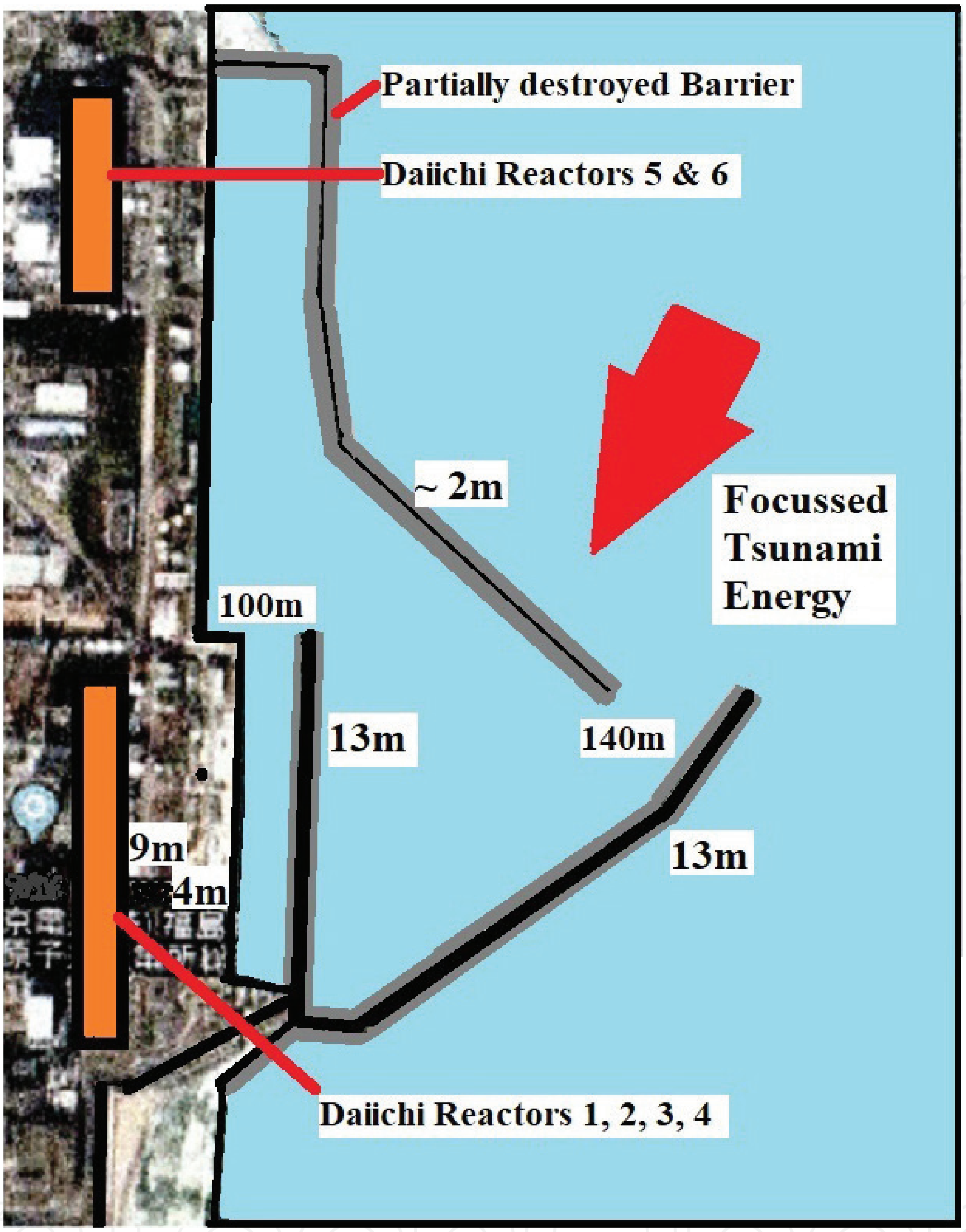

Figure 2. Top view of Fukushima Daiichi Reactors with two intact sea walls and one remnant wall. The two walls focused the tsunami energy and led to increased secondary tsunami water wave.

the reactor buildings. Cooling the fuel rods was essential even when the reactors had been switched off. The helplessness of the owner's management became obvious when on TV one could observe helicopters dropping water onto the reactor ruins and ships which directed water guns toward the reactors. Insufficient cooling therefore could not prevent the meltdown of the fuel which then fused through to the bottom of the reactor pressure vessel and partially went through to the primary containment vessel of concrete 7.6 m thick where it is assumed to have stopped.

Attempts to investigate the situation inside the reactors by muon scanning and by a remote-controlled camera have proven the meltdown of the fuel and its lowering to the concrete containment vessel.

A large amount of radioactive materials of 130 petabequerels has been released into the air from March 11 to April 5, 2011, which corresponds to 11% of the Chernobyl emissions. Accordingly, the heavily contaminated area around Fukushima corresponded to 10–12% of the Chernobyl area. The sea was contaminated by about 84 kg of cesium-137 corresponding to 27 petabequerels whereby 82% flowed into the sea before April 8, 2011. This contamination consisted of controlled and uncontrolled release of contaminated water, of surface water flowing over contaminated soil and of airborne radioactive particles that entered the sea by rain. The attempts of the owner’s company to stop the flow of contaminated water to the sea by a 30 m-deep wall in the ground and by an underground ice wall have been only partially successful. On September 10, 2015, the typhoon Etau caused an uncontrolled flow of contaminated water into the ocean.

Studies have shown that contamination of the ocean as measured would not have long-term effects on health due to the powerful Kuroshio current and the dilution in the wide Pacific. The contamination through the air into the ground requires the collection of radioactive soil in millions of plastic bags in order to facilitate the return of the evacuated people to their homes.

The World Health Organization (WHO) and other institutions and organizations evaluated the health risks which are expected to be small for most of the population due to the estimated small amount of received radiation [12]. The main health effects have been observed with the evacuated people of which 1600 died from stress and suicide, not from cancer. The main cause of these fatalities is due to the accident and the hectic exaggerated evacuation, but a certain responsibility have the green-political parties, organizations and media with excessive reports about the accident and risks. The extremely low personal value of 1 millisievert (mSv) per year from artificial radiation in Japan is in contrast to international annual doses of 20 mSv as accepted by the International Commission on Radiological Protection (ICRP), the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and the World Health Organization (WHO). Due to the low received radiation, no significant health effects are expected for the population of cities within the 20-mile zone around the Fukushima plant. The March 2015 thyroid gland investigation of 300,000 children effectively showed no noticeable cases.

There are enormous costs for the owner company and for Japanese taxpayers for compensation, decontamination, dismantling the reactors and radioactive waste storage, exceeding 187 billion US dollars. The main consideration will be Japan’s energy future in view of lack of resources and resistance from the population. In view of the crucial importance of nuclear energy for Japan’s future, as a personal responsibility, opponents of nuclear energy could consider reducing their electricity consumption during periods of electricity shortage.

Emergency actions and consequences for reducing the aftereffects in case of a future, most-improbable nuclear accident are discussed later.

4. Discussion on the possible management problems after March 11, 2011

4.1. Missed chances to reduce the contamination level

The nuclear accidents in Chernobyl and in Fukushima have caused huge contamination of cities, villages and land and had necessitated the evacuation of ten-thousands of people a fraction of which in case of Chernobyl had received hazardous radiation.

In case of a such nuclear accident, there are two aspects which require immediate action:

1. Can the fission rate and the development of uncontrolled heating of the fuel rods be stopped from the control room or by remote actions to lift the fuel rods or by introducing neutron-absorbing elements or compounds based on boron, silver, cadmium and indium combined with intensive cooling, decisions to be made immediately by an experienced reactor engineer.
2. In case of fire or escaping flames and clouds, the collateral damage by widespreading of radioactivity has to be minimized by very intense water spraying using any water resources, be it from nearby lake or river or sea and using water pumps and high-power water guns powered from pre-installed and mobile diesel generators. When a natural water source cannot be reached, then the installation of a nearby pond of sufficient volume should be arranged near all reactors. Contamination of the sea is less harmful than contamination of cities, villages and landscapes. The optimum would be sea reservoirs built with the Tsunami-Flooding Barriers [11]. With visible installations for the water guns outside the reactor building, with watering exercises and with proper information, people can be assured that evacuation will not be required in the future, even in case of an accident.

If a long-lasting fire occurs as in Chernobyl, where the graphite moderator burnt and sent radioactive clouds very high so that contamination spread over large distances or in case of Fukushima, where the cloud left the reactor building and was carried by wind, intensive suction should be considered. **Figure 3** schematically shows the reactor building with attached large-diameter steel pipes which collect the cloud by a powerful ventilator of at least 5000 m^3 per hour depending on tube diameter. A sprinkler system condenses the radioactive vapors and particles, and this contaminated water should then flow into the sea reservoir or into a basin. In case of Fukushima, this contaminated water should in the first phase have been transported by long pipes to the Kuroshio current where it is diluted. In the second phase, the gaps of 100 and 140 m between the existing seawalls/breakwaters could have been closed and water could have been pumped out to the basins where it could be collected and stored for later treatment. The intense spraying followed by the suction activity would have reduced the extended radioactive spreading and thus the evacuation requirements. Such suction systems could also be useful in case of accidents and fires in chemical factories and in oil refineries.

Reactor surrounding should always be covered by a thick concrete layer with a slope of 2–3° in the direction of the sea or the basin, so that all water is controlled and collected and the soil cannot be contaminated.

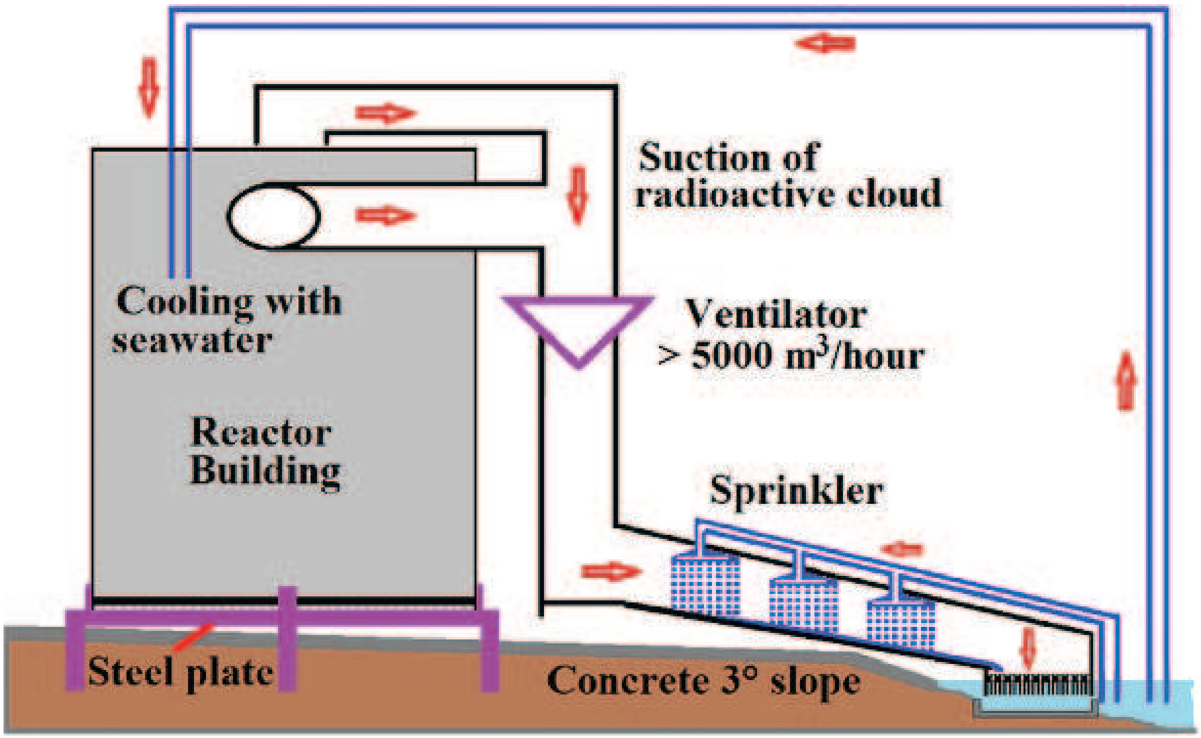

Figure 3. Schematic view of suction of radioactive cloud and sprinkling with seawater.

The groundwater should never become a problem for the reactor by installing deep watertight barriers around the reactor area, before the reactor starts to work.

The successive hydrogen explosions, which destroyed a part of the reactors and their roofs, should have been prevented by hydrogen detectors, which raise an alarm and which activate valves for high-pressure injection of nitrogen or CO_2. Hydrogen concentration should always be kept below the explosion level of 4% in air, this value depending on humidity and other factors. The alternative of Passive Autocatalytic (Hydrogen) Recombiners (PAR) [13] does not require electricity to operate and has been installed in some reactors worldwide. PAR had been applied in the Three-Mile-Island accident (March 28, 1979) to reduce the hydrogen content in a hydrogen bubble inside the reactor chamber to prevent a large explosion. Hydrogen removal works even in the presence of CO which is frequently formed in fires [14].

4.2. The contaminated water problem

After the initial weeks following the accident, large amounts of cooling water had been pumped into the reactors, for example, 300 metric tons per day, which initially was further diluted with 400 m^3 groundwater. Despite large efforts taken to reduce the influx of groundwater, it could not be stopped. Half of the water returning from reactor cooling was filtered and partially decontaminated and returned for cooling, and the other half of 200 m^3 was collected daily in large storage tanks in the plant surroundings for later treatment. A fraction of this tank collection is shown in **Figure 4**.

Decontamination of water was problematic. Equipment from France, USA and Japan had been applied using reverse osmosis, adsorption by zeolites or evaporation of salt water.

Figure 4. Fraction of tanks with >300,000 m3 contaminated water at Fukushima power plant.

Problems have been errors in handling of valves, repeated leakages of connections and pipes and stopped pumps which could not be re-activated. Reference [15] gives some details of the dramatic water contamination problems. From outside it looks like small-scale attempts to solve large-scale problems.

With the existence of the three seawalls in front of the coast of Fukushima plants, there is the possibility to connect the ends of these seawalls by new walls of 100 and 140 m length to form three basins as shown in **Figure 5**.

To construct these barriers by conventional technology with rubble mound foundations and top caissons [8] or to build concrete walls would be a lengthy process and not provide highest safety. Recently, two methods have been developed which allow efficient construction of submerged barriers at reduced costs [11, 16]. In a first step, deep "beds" are dredged into the bottom of the sea with the depth depending on the sea ground (rocks, gravel, sand, mud). In the double-pontoon technology, two separated pontoons start from a ramp road at the coast and allow to move trucks. The first truck inserts a stainless steel (316L, 316LN, 1.4429) fence outside the pontoons into the sea, for instance, stable fence of Geobrugg, Romanshorn, Switzerland. The next truck inserts alternating rocks and concrete in the gap between the pontoons into the sea. Distance holders allow to erect a stable vertical wall of 6 –20 m width. These central pontoons hang on steel beams between assisting pontoons in order to carry the heavy weights. The second technology uses long tall cylinders of more than 100 m length fabricated in the harbor and floated to the site where they are inserted into the sea bed and filled with rocks, sand, and so on. These walls named Tsunami-Flooding-Barriers (TFB) are vertical toward the sea and thus reflect the impulse waves of tsunami. They extend about 10 m above sea level and carry a service road on top which is protected against storm waves by replaceable surge stoppers (parapets) [11].

Hydrodynamic modeling [17] of the action of TFB barriers by coupling the far-field depth-averaged Boussinesq-type model pCOULWAVE of Lynett et al. [18] with a near-field

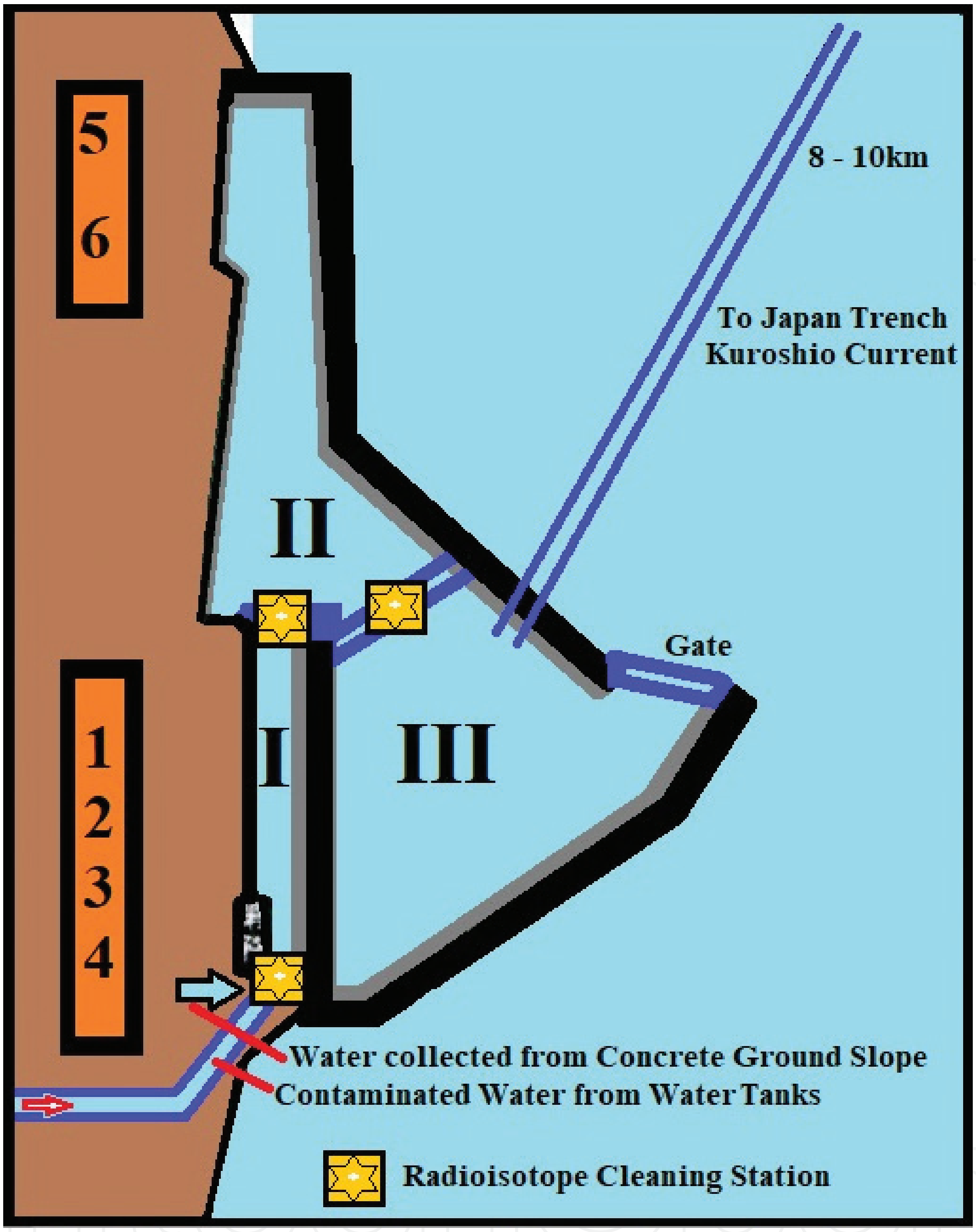

Figure 5. De-contamination of water and release to the sea, schematic top view.

Navier–Stokes Computational Fluid Dynamics CFD model [19] allowed a more accurate simulation of the fluid–structure interaction. The high efficiency of the TFB to reflect the tsunami impulse waves and the storm-wave reflection of the surge stopper (parapet) is confirmed. Furthermore, the loading onto the vertical walls has been estimated [17].

The TFB concept could find wide application as it protects coastal cities and industries, but also beaches against tsunami and against flooding from tropical storms like hurricanes and typhoons. Also, flora and fauna could be saved in case of an oil-spill. In the past 20 years, these natural catastrophes have caused a quarter of a million fatalities and damages exceeding 500 billion US dollars mainly in Japan, Indonesia, Malaysia, Philippines, Sri Lanka, India and at the east coast of USA. In Japan, the TFB would have prevented in 2011 the 19,000 tsunami fatalities and 300 billion US dollars damages with destroyed houses and, of course, it would have prevented the Fukushima catastrophe. For the countries with risk of storm and tsunami flooding, such a large project would stimulate the building, transport and steel industries and would occupy thousands of workers and thus would have a significant impact on the economic development.

Now Japan started a large project to build tall concrete walls, with height up to 14 m and width up to 46 m, along the coast of Honshu. The estimated costs are higher than building the TFB walls submerged in the sea at large distances from the coast, thereby not disturbing the view of the ocean for coastal citizens and for tourists. Fishermen would keep access to the sea. The population has formed a large resistance against the Japanese great wall of which only partial protection can be expected in case of a large tsunami which on March 11, 2011, had a reported maximum height of 38 m. The 500 km great wall along Honshu coast would consume 23 million m^2 land area plus land surface for the required construction and service roads.

The water from the three basins (shown in **Figure 5**) is pumped out before their bottom is covered with a thick concrete layer. Contaminated water from reactor cooling, from the collecting point of the sloped concrete ground and from the storage tanks flows into basin I. After passing through the first decontamination stage, it enters basin II and then through the next decontamination step to basin III. After checking the low residual radioactivity from cesium-134, cesium-137 and Sr-90, the remaining radioactivity will be from tritium. This has a short half-life time of 12.3 years and anyhow occurs naturally in seawater, formed by cosmic rays, in extremely low concentrations of hydrogen(10^{-18}). Therefore, there is no risk if this tritium-containing water of basin III is transported through long pipes into the Kuroshio current near the Japan trench which has a depth of 10 km. The short half-life time and the dilution effect will prevent the detection of tritium supply from Fukushima.

In view of the large quantity of contaminated water in the 1000 m^3 tanks, a pre-decontamination step could be to introduce by stirring an isotope-adsorbing agent (e.g. zeolite) into the tank and letting it settle by gravity for sufficient time so that the deposit mud on the tank bottom can be sucked by slowly sweeping long tubes and then compacted by a drying process. An alternative could be salting-out and precipitate cesium-137 compounds. This would reduce the contamination level of the collected water and facilitate the final treatment.

4.3. Storage of radioactive waste

The storage of radioactive waste consisting of used fuel rods, of cut pieces of the reactor chambers, of rubble from the reactor foundation and building and from contaminated soil collected from the reactor surrounding is a technological challenge but mainly a political problem. Therefore, a site near the reactor ruins could find minimum resistance from the public. Large amounts of concentrated radioactive waste were collected and transported to the temporary storage facility.

After solving the water problem, the three sea basins with the thick concrete bottom are pumped empty and used as a dump for radioactive waste with the final goal of reclaiming new land. The rubble caused by the reactor explosions, the drums with sludge from the decontamination process, all the plastic bags with collected contaminated soil and all contaminated material presently stored in Interim Storage Facilities will be transported to this dump. Finally, the debris from scrapping the destroyed reactors 1–4 could be deposited in these basins. The concrete debris could partially be milled and used for new concrete buildings.

The schematic cross-section view (**Figure 6**) of this “Fukushima dump” shows the original reactor before dismantling as well as the dump in the basin which is protected against flooding with the Tsunami-Flooding-Barrier. In view of keeping radiation and the elevated temperature, the molten fuel rods, after sufficient cooling in 30–80 years, should be enclosed in tubes of a metal which is relatively stable against oxidation at ambient oxygen pressure and temperature and limited humidity. Theoretically, the best materials for encapsulation would be the noble metals silver, gold and platinum but their high value would make them too attractive and thus cause a risk for the storage site for radioactive waste. **Figure 7** shows the temperature dependence of the thermodynamic stability of oxides of metals which could be applied as container for radioactive material. This Ellingham-type diagram [20], extended for CO–CO_2 and for H_2–H_2O gas ratios by Richardson and Jeffes [21], is discussed in [22]. Practical values for temperature can be obtained by a straight line passing from one of the three points (O, H, C) on the left margin to the oxygen partial pressure or the gas ratios on the scales on the right side of the diagram and hitting the stability line of the specific metal. Iron-nickel-chromium alloys (stainless steel) and lead could be considered, and copper is foreseen for enclosing radioactive material in Sweden.

Depending on the shape of molten fuel rods within their surrounding they could be cut to pieces and enclosed in capsules or in thin tubes of one of the suitable metals and then sealed. In any case, the fuel-rod-material should be safely stored in a site from which it can be recovered by future generations to use the significant energy remaining in the fuel rods.

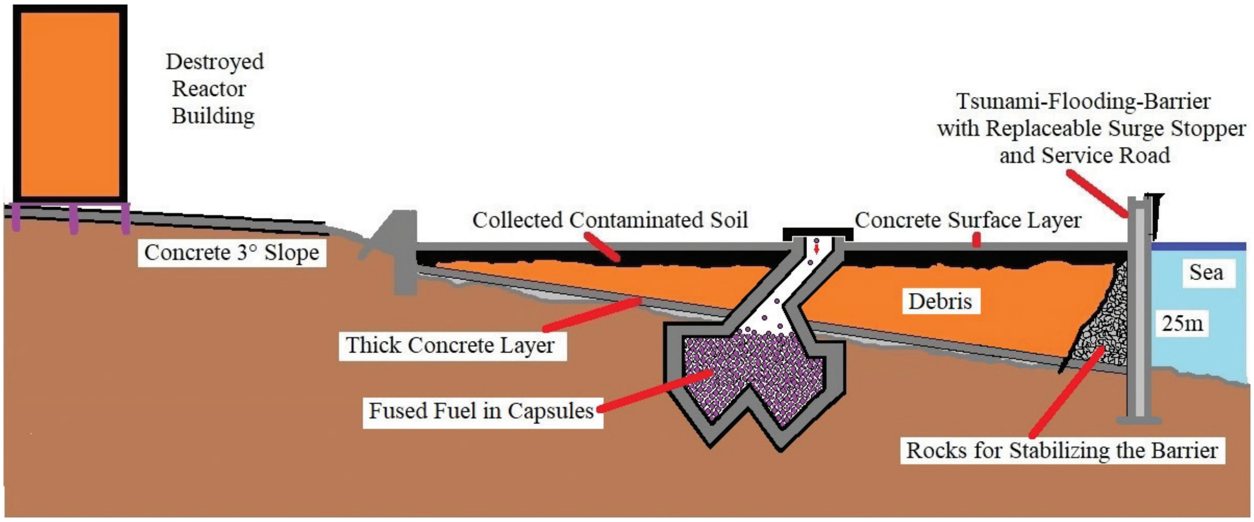

Figure 6. Storage of the rubble of the dismantled reactor building and of the collected contaminated soil in basin I which before had been emptied and covered with a thick concrete layer. After sufficient cooling the fused fuel is encapsulated and inserted into the cavity. Finally, with concrete cover on top new land is generated. The Tsunami-Flooding-Barrier protects against future tsunami and against flooding from typhoon. (Schematic cross section).

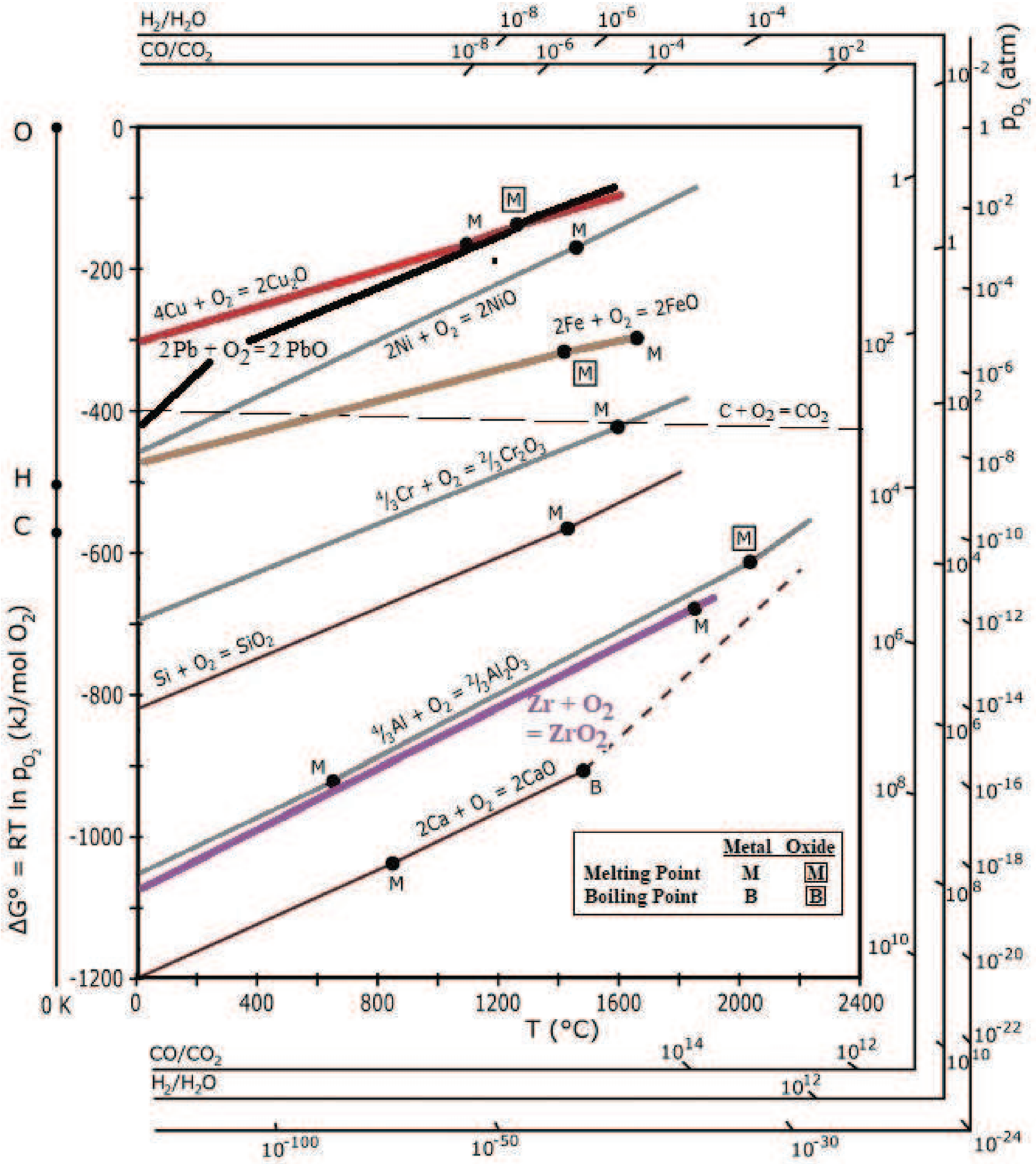

Figure 7. Standard free energy of formation of metal oxides as a function of temperature.

These tubes and capsules are then introduced through an opening shown in **Figure 6** into a barium-concrete chamber prepared below the bottom of the dump. Leakage to the ocean will be excluded when the material with highest radioactivity is stored in basin I and basins II and III also have been emptied, provided with a thick concrete layer, and used as dry dump for less-contaminated waste.

The original sea walls with seaside slopes will be complemented with Tsunami-Flooding-Barriers [11, 16] with the vertical wall on the seaside so that future tsunami and typhoons cannot harm the deposit development. Protection against heavy rain by a cover and against storm waves by a large floating fence in front of the TFB barriers [23] will prevent disturbance of the dump activities. With proper planning the sequence and the locality of the radioactive waste, the final radioactivity on top of the dump will not be higher than the natural value in Japan.

With this procedure the total costs for dismantling the reactors, for decontamination, for interim storage and for final storage of about 100 billion US dollars can be significantly reduced.

5. Conclusions and outlook

The Fukushima accident (and also the former Three-Mile-Island and Chernobyl catastrophes) has demonstrated that no engineer and manager with wide experiences and deciding power have been on site. In the case of Fukushima, urgent actions for very intense water spraying the fire and the cloud, for suction of the cloud, for manually opening the valve of the passive cooling system and for covering the ground with a thick concrete layer with slope of 2–3° depended on decisions of the owner's headquarters in Tokyo. This was concentrated on the internal problems of the reactors, on political and publicity pressure and anyhow was under enormous stress and was not aware of the consequences for the local population and of the following national and international consequences. The experiences from the Three-Mile-Island accident and the recommendations have been summarized in Ref. [24].

Competent reactor engineers should be educated who learn, besides nuclear technology, about all possible chemical reactions, corrosion and electro-corrosion, properties of the involved materials, failure of materials and components, aero-and hydrodynamics, meteorology, and so on.-.

Another question is about the possibility for emergency interruption of nuclear fission by cadmium-indium alloys inside thin silver tubes and boron carbide/boron nitride/boron oxide composite tubes, whether such tubes can be inserted into Type-II generators until the safe generation III/III+ and IV reactors with a four-fold redundancy of emergency equipment will be developed.

It has become clear that the Fukushima accident could have been prevented if in the planning stage the worst-case scenario would have been considered by the plant owner and by the responsible ministry. Even after the accident caused by the unexpected tsunami, the collateral damages could have been mitigated if a competent foresighted management had timely initiated the described procedures. An international emergency team of top engineers with multidisciplinary and industry experience could assist worldwide in case of heavy nuclear, chemical, fire and other catastrophes.

Anyhow, with the development of the safe generation III and IV reactors the nuclear energy will become more dominating and increasingly replace the fossil energy in view of limited resources, of the CO_2 climate problem and of overall safety concerns. The new high-temperature reactors and fast breeders will have a significantly higher efficiency, consume less fuel and produce less radioactive waste. The renewable wind and solar energy is faced with the electricity storage problem, so that nuclear energy is more and more needed as reliable band energy. Frequently, the storage of radioactive waste is regarded as a problem with concern of the population regarding the site for a deep geological deposit. Recently the concept of a safe deposit the waste in a lonely mountain site has been developed which will be economic and faces less political resistance [25].

The common features of the three nuclear accidents (Three-Mile-Island 1979, Chernobyl 1986 and Fukushima 2011) are the combination of personnel error and mistakes, deficiencies in reactor and safety component design, and component failures. Charles Perrow has formulated the "Normal Accident Theory" that in processes of huge complexity, accidents are due to "unanticipated interaction of multiple failures in a complex system" [26–28]. Thus, for nuclear reactors with their enormous complexity all possible failure combinations should be analyzed and precautions with sufficient redundancy found before the plant is switched on. Of great importance is also multidisciplinary high-level education of reactor engineers and reactor managers and adequate training of operators to reduce accidents and their consequences.

It is hoped that the described experiences will assist in planning future reactors and in reducing collateral damage in case of a future accident which, however, hopefully will not occur.

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