

# Preliminary Lessons Learned from the Fukushima Daiichi Accident for Advanced Nuclear Power Plant Technology Development

## A. Introduction

The IAEA Report on Reactor and Spent Fuel Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant<sup>1</sup>, which is based on the deliberations of an International Experts Meeting on the same topic in March 2012 in Vienna, emphasizes that the application of the defence in depth concept should be improved at two levels — the prevention of severe accidents, including through decay heat removal from the reactor core and spent fuel, and the protection of containment integrity. This paper reviews technological features — some already broadly deployed, others used only in new designs — that address both levels and describes safety systems that can create options and extra time in an accident characterized, like the Fukushima Daiichi accident, by the loss of power, the loss of cooling water flowing through the core and the loss of the ultimate heat sink. These technologies offer ways in which designers can increase both the diversity of core and containment cooling systems and the ways those systems are powered, i.e. gravity, compressed gas, AC power, DC power and natural circulation.

Section B summarizes passive core cooling systems to remove decay heat from the reactor core in an emergency. Section C summarizes passive systems for cooling the containment and suppressing pressure. In fact, the highest levels of safety and reliability could result from carefully designed combinations of active and passive systems.

Section D summarizes further technology options related to strengthening and venting containments, preventing hydrogen explosions, hardening instrumentation against radiation and cooling spent fuel.

## B. Passive Reactor Core Cooling Systems

Passive core cooling systems can cool a reactor core without requiring AC electric power. They rely on combinations of gravity, natural circulation, DC power and compressed gas to transfer heat to either evaporating water pools or to structures cooled by air or water convection. Six variations are summarized in this section.

### B.1. Pressurized core flooding tanks (accumulators)

Pressurized core flooding tanks, or accumulators, are already used in some currently operating reactors as part of their emergency core cooling systems. They typically consist of large tanks about 75% full of cold borated water (Fig. B-1). The remaining volume is filled with pressurized nitrogen or an inert gas. The contents of the tank are isolated from the reactor by check valves that are held shut during

<sup>1</sup> <http://www.iaea.org/newscenter/focus/actionplan/reports/spentfuelsafety2012.pdf>

normal operation by higher pressure in the reactor. In the event of a Loss-of-Coolant Accident (LOCA), the reactor pressure will drop, opening the check valves and discharging the borated water into the reactor vessel. This is a one-time discharge of cold water to buy time, of the order of minutes, prior to longer term emergency core cooling systems starting up. Accumulators do not provide continuing heat removal.

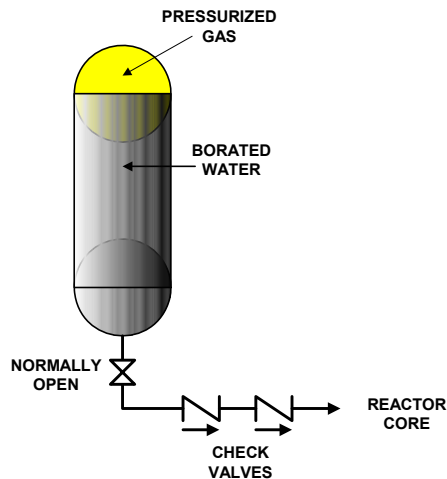


FIG. B-1. Pressurized core flooding tank (accumulator).

## B.2. Elevated tank circulation loops (core make-up tanks)

Some new designs now under construction include elevated tank circulation loops (Fig. B-2). The tank is filled with cold borated water and normally isolated from the reactor by a valve in the discharge line at the bottom of the tank. The inflow line at the top of the tank is connected to the reactor cooling system. In an emergency, the bottom valve is opened to allow the cold borated water to flow into the loop. The cold borated water flows down into the core where it is heated, rises and flows back into the tank through the inflow line. Since the tank includes no heat exchangers or other means to remove heat, core make-up tanks also provide only short-term discharges to buy time for other cooling systems to start up. They do not provide continuing heat removal.

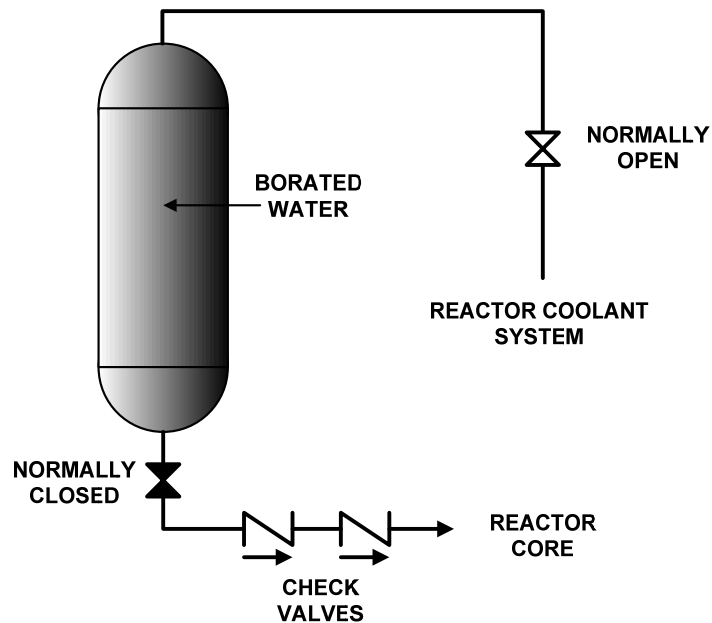


FIG. B-2. Elevated tank circulation loops (core make-up tanks).

### B.3. Elevated gravity drain tanks

Elevated gravity drain tanks are like the accumulators described in Section B.1, except they are driven by gravity rather than pressurized gas. They therefore are effective when the pressure in the reactor core is not greater than the weight of the water in the tank. They may be ineffective if the core is uncovered and generating high pressure steam. In some advanced designs, the volume of water in the tank is sufficiently large to flood the entire reactor cavity. Elevated gravity drain tanks also provide only a one-time discharge of water to buy time.

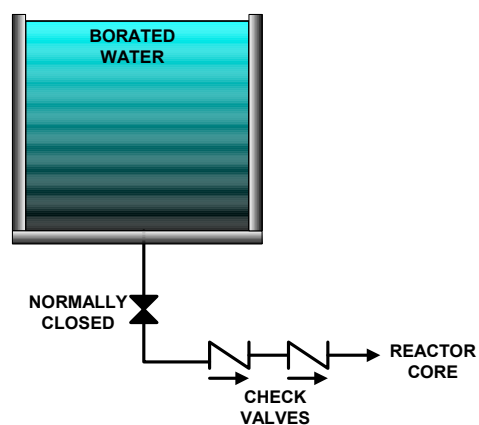
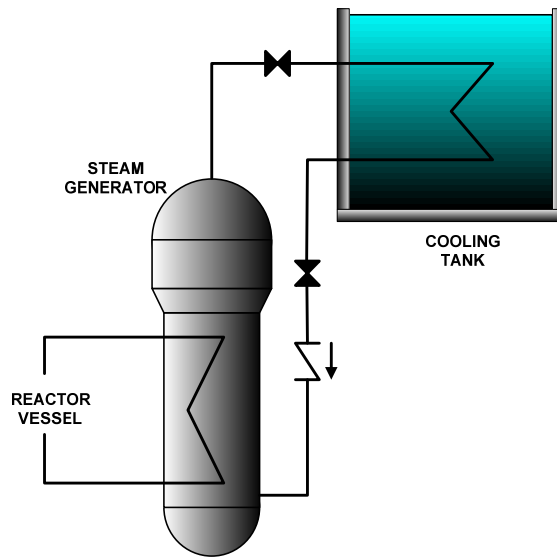


FIG. B-3. Elevated gravity drain tank.

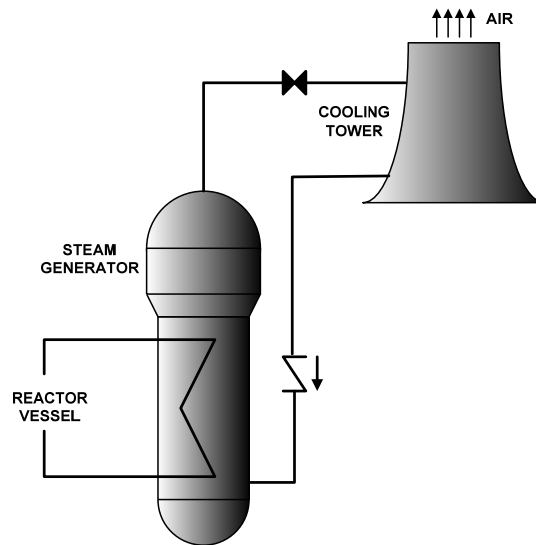
### B.4. Passively cooled steam generator natural circulation

Some advanced pressurized water reactor (PWR) designs incorporate an emergency passive, natural circulation cooling loop to remove heat from the steam generators either to a large water-filled cooling tank (Fig. B-4) or to the air through cooling towers (Fig. B-5). Both options could provide continuous rather than short-term cooling during an emergency although a cooling tank would require refilling as its contents evaporate, depending on the heat load, over a period ranging from less than a day to

several days. Both options would only be effective if the emergency left the cooling loops that remove heat from the core to the steam generators undamaged.



*FIG. B-4. Core decay heat removal using a passively cooled steam generator (water cooled).*

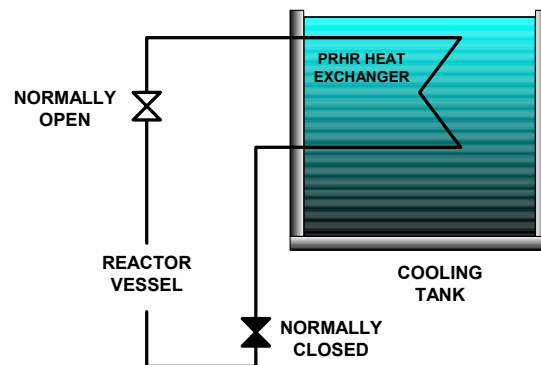


*FIG. B-5. Core decay heat removal using a passively cooled steam generator (air-cooled).*

## **B.5. Passive residual heat removal (PRHR) heat exchangers**

PRHR heat exchangers are incorporated into several advanced PWR designs (Fig. B-6). They work like the passively cooled steam generator natural circulation loops described in Section B.4, except that they would remove heat directly from the reactor core, not the steam generators. They would thus

provide continuous cooling during an emergency, with the caveat noted above that the cooling tank would require refilling as water evaporates, and would be effective even if the emergency had damaged the cooling loops that remove heat from the core to the steam generators.



*FIG. B-6. Core decay heat removal using a water cooled passive residual heat removal heat exchanger loop.*

## **B.6. Passively cooled core isolation condensers (steam)**

Passively cooled core isolation condensers (Fig. B-7) are included in early boiling water reactor (BWR) designs, including Unit 1 at the Fukushima Daiichi plant. The steam generated in the core is sent to isolation condenser (IC) heat exchangers in large water pools. The steam is condensed, and the condensate returns by gravity to the bottom of the reactor vessel to complete the loop. The system thus provides continuous, although limited, cooling to prevent the reactor from over pressurization. For Unit 1 at the Fukushima Daiichi plant, the IC failed to provide adequate cooling because the batteries needed for its operation were flooded by seawater<sup>2</sup>. The shutdown cooling system was unavailable because AC power had been lost.

<sup>2</sup> For more detail, refer to reference 3, P.118

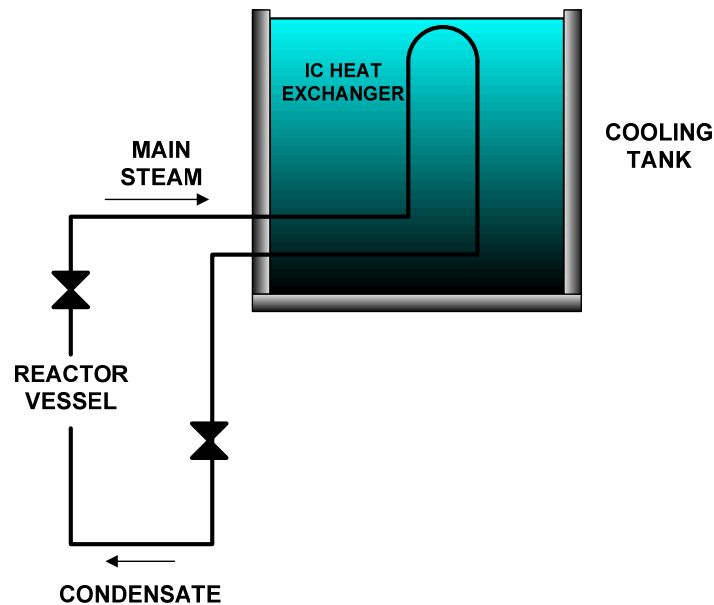


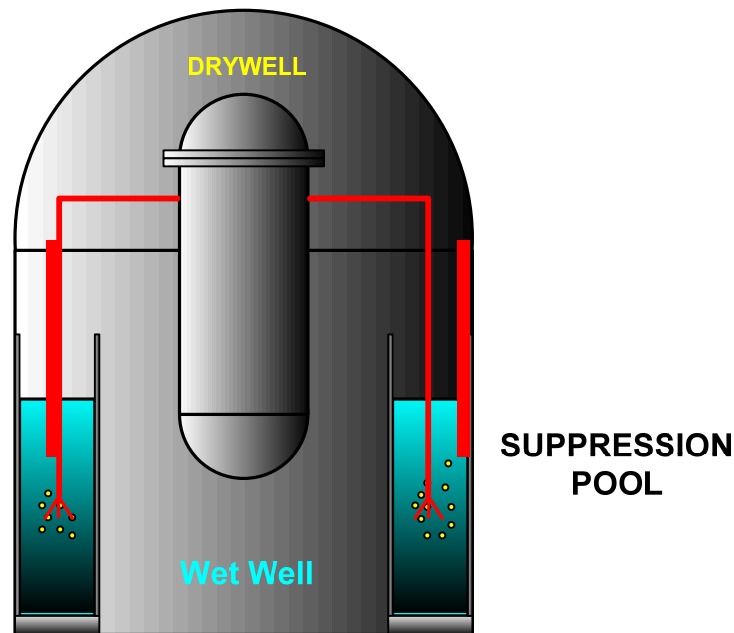
FIG. B-7. Isolation condenser cooling system.

## C. Passive Systems for Containment Cooling and Pressure Suppression

Passive systems can also be used to cool the containment and suppress pressure in the containment without requiring electric power. Three variations are summarized in this section.

### C.1. Containment pressure suppression pools

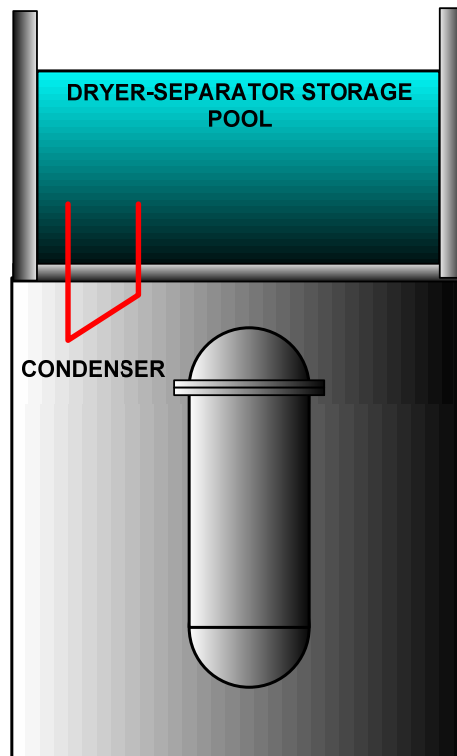
Containment pressure suppression pools (Fig. C-1) have been used in various versions in BWRs for many years, including at the Fukushima Daiichi plant. They work by forcing the steam collecting in the containment (also referred to as the drywell) through large vent lines submerged in water in suppression pools. The steam condenses to a much smaller volume thus suppressing pressure increases in the containment. Longer term heat removal to continue to suppress pressure increases requires active systems. During the Fukushima Daiichi Accident, the longer term, larger volume, shut down cooling system at Unit 1 and residual heat removal system at Units 2 and 3 failed because of the absence of AC power.



*FIG. C-1. Containment pressure reduction following a LOCA using steam condensation in suppression pools.*

## **C.2. Containment passive heat removal / pressure suppression systems**

This approach uses natural circulation cooling loops and an elevated pool as a heat sink. Figures C-2, C-3 and C-4 show three variations. The forces driving the natural circulation may be low in all variations, and careful system engineering is needed to ensure sufficient flow. Long-term cooling would require replenishing the water that would evaporate from the elevated pool. Figure C-2 shows a condenser with inclined tubes connected with a pool on the top of the containment. Steam vented into the containment would condense on the tube surfaces, which would reduce the pressure and temperature in the containment. Cooling water would flow because of natural circulation driven by the heated water rising in the inclined tubes. This system has been implemented in a few new operating reactors. Figure C-3 shows a closed loop in which the condenser in the containment is connected to an elevated heat exchanger in an external cooling pool, thereby establishing natural circulation in the cooling loop. Variations on this system were added to a number of reactors following the Three Mile Island accident in 1979 — in some cases as back-fits and in others as features in newly built reactors. In the third variation (Fig. C-4), which is not yet incorporated in any operating reactor, the cooling loop takes steam directly from the containment, condenses it in tubes in the elevated pool which reduces the pressure and temperature in the containment, and returns the condensate to a separate zone in the containment referred to as the wet well.



*FIG. C-2. Containment pressure reduction and heat removal following a LOCA using steam condensation on condenser tubes.*



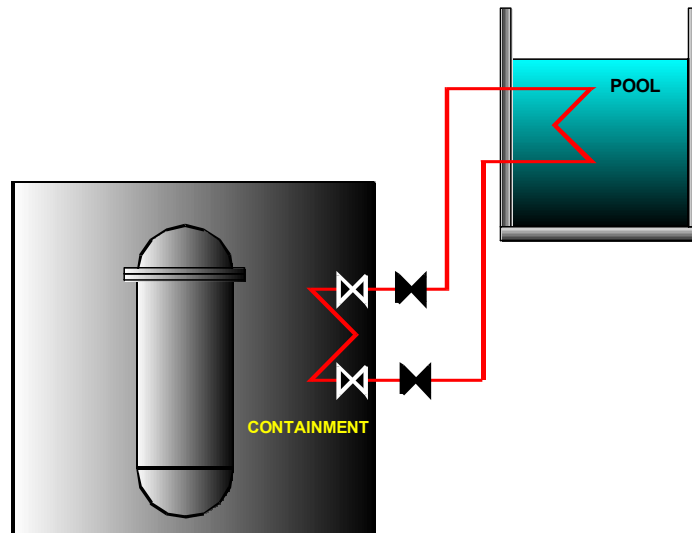


FIG. C-3. Containment pressure reduction and heat removal following a LOCA using an external natural circulation loop.

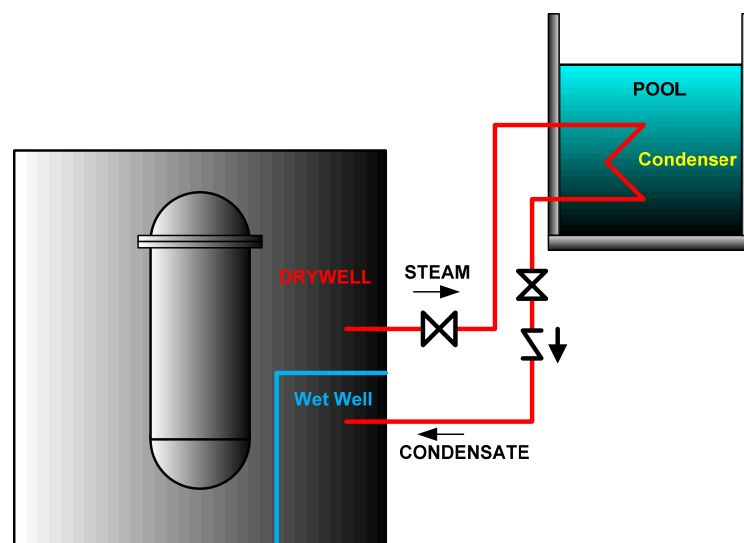
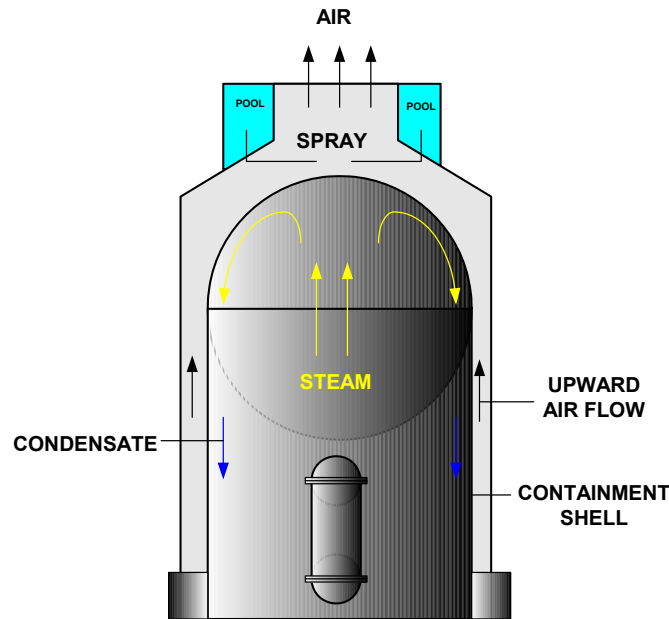


FIG. C-4. Containment pressure reduction and heat removal following a LOCA using an external steam condenser heat exchanger.

### C.3. Passive containment spray systems

In the design shown in Fig. C-5, following a LOCA the steam in contact with the inside of the steel containment would condense. Heat would be transferred through the containment wall to the air outside the wall, which would rise as it is heated. It would be discharged through the top of the structure and replaced by cooler air continually entering at the bottom. A pool on top of the

containment would provide a gravity driven spray of cold water to accelerate the cooling if DC power is available.<sup>3</sup> This system is included in some new plants currently under construction.



*FIG. C-5. Containment pressure reduction and heat removal following a LOCA using a passive containment spray and natural draft air.*

## D. Further Technology Options

### D.1. Containment design

The containment is the last barrier to prevent large radioactive releases from a severe accident. Technological improvements beyond the designs used in the Fukushima Daiichi plant include pre-stressed or reinforced single concrete containments with steel liners, cylindrical and spherical steel containments, and pre-stressed double containments with and without steel liners. These allow higher design pressures and lower leakage factors. Some designs also include core catchers to collect molten core material that melts through the reactor vessel and prevent it from escaping while also spreading it out to make it easier to cool. Each of these features is included in one or more of the advanced designs now in operation or under construction.

### D.2. Prevention and mitigation of hydrogen explosions

During the Fukushima Daiichi accident, hydrogen explosions occurred in the reactor buildings of Units 1, 3 and 4. To prevent the accumulation of a dangerous amount of hydrogen in an accident, some more recent designs include hydrogen igniters and/or autocatalytic recombiners. Hydrogen

<sup>3</sup> Power is needed because, to start the gravity flow, an actuator must explode to open the valve that holds back the elevated water supply. The signal to the exploder comes from a melting fuse located below the reactor vessel, and because the signal is sent automatically, without human action, the system is considered passive. Nonetheless, DC power is needed for the signal to be sent from the fuse to the exploder.

igniters require power and are thus active, not passive, systems. Autocatalytic recombiners do not require power and are therefore passive.

### **D.3. Containment venting systems**

To avoid dangerous pressure increases and hydrogen accumulations, it should be possible to vent the containment even under difficult conditions. During the Fukushima Daiichi accident, remote controls in the control room for venting were lost due to loss of power, and local manual venting was delayed due to high levels of radiation, and absence of electricity and compressed air necessary to operate valves.<sup>4</sup> Several currently operating nuclear power plants, however, have been, or are being, retrofitted with filtered containment venting systems. These create the option of venting to reduce the pressure and hydrogen levels in the containment without also releasing large amounts of fission products. Such systems could have avoided the delays during the Fukushima Daiichi accident but they could not have avoided the delays due to loss of electricity and compressed ‘control air’ for valve operation.

### **D.4. Instrumentation hardened against high radiation levels**

During the Fukushima Daiichi accident, without power for instrumentation, operators could not fully monitor reactor conditions. It is essential to assure that instrumentation can survive the high temperatures, pressures, and radiation levels resulting from severe accidents, and that necessary power is available for essential instrumentation systems. The best improvement currently available is simply to add better shielding for vulnerable I&C systems. However, current research into radiation hardening has resulted in breakthrough developments of more robust cables, gauges, instrumentation, and electronic systems. Further research and development aims at the availability of hardened components for both new designs and back-fits in existing power plants.

### **D.5. Spent fuel cooling**

Although there was very limited damage to spent fuel during the Fukushima Daiichi accident, the accident did focus attention on possible scenarios that could have resulted in more severe damage. Because the pressures and temperatures associated with spent fuel storage are much less than those in the reactor, technological options for improving the diversity and reliability of spent fuel cooling and containment during an accident are relatively straightforward. Some advanced designs already incorporate emergency systems for cooling spent fuel and more robust pool structures with diverse approaches to monitoring and cooling. For future plants, spent fuel pools could be housed in containment-like structures.

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<sup>4</sup> Interim Report of Investigation Committee on the Accident at Fukushima Nuclear Power Stations of Tokyo Electric Power Company, P. 181-183 and P. 232-235

## REFERENCES

1. INTERNATIONAL ATOMIC ENERGY AGENCY, Mission Report The Great East Japan Earthquake Expert Mission, IAEA International Fact Finding Expert Mission of the Fukushima Dai-ichi NPP Accident following the Great East Japan Earthquake and Tsunami, IAEA, Vienna (2011).
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3. INVESTIGATION COMMITTEE ON THE ACCIDENT AT THE FUKUSHIMA NUCLEAR POWER STATIONS (GOVERNMENT COMMITTEE OF JAPAN), Report on the Accident at Fukushima Nuclear Power Stations at Tokyo Electric Power Company, Interim Report, December 2011: <http://www.cas.go.jp/jp/seisaku/icanps/eng/interim-report.html>
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