Understanding Boiling Water Reactors by Ir Dr Vincent HO

The magnitude 9 earthquake that struck of Sendai, Japan, on 11 March 2011 was the biggest earthquake to hit that country in 150 years and one of the five most severe quakes in the world since 1900. This earthquake and the ensuing 13-m high tsunami caused thousands of fatalities and billions of dollars worth of damage. The disaster has also shaken the nuclear power industry by causing multiple failures at Fukushima I (Daiichi) nuclear power station (福島第一原子力發電所). The subsequent atmospheric release of radioactive materials makes the event the worst nuclear accident since Chernobyl and the only nuclear accident involving damages to multiple reactor cores at the same site.

Fukushima I was the first nuclear plant constructed and operated entirely by the Tokyo Electric Power Company. With six units having a combined capacity of 4.7 GW, Fukushima I was one of the 25 largest nuclear power stations worldwide and accounted for about 9% of total nuclear power production in Japan. Reactor unit 1 at Fukushima I started commercial operation in 1971, while Units 2 to 6 came into operation from 1974 to 1979. With a design life of 40 years, unit 1 was initially scheduled for shutdown in early 2011 but was granted a 10-year extension in February 2011. While the event continues to unfold in the coming weeks, this article examines the design of nuclear reactors similar to Fukushima I.

Boiler – the Other Light Water Reactor

Light water nuclear power plants generate power in a similar way to ordinary power plants except that they use nuclear fission as the heat source to produce steam, with water acing as coolant to prevent core melt and as a moderator to slow down the neutrons in order to sustain nuclear fission.

Unlike fossil fuels, spent nuclear fuel continues to emit heat as it decay even though the nuclear reaction has been terminated. Nuclear fuel removed from a reactor core must be continuously cooled and covered with water to prevent overheating due to this decay heat and radioactive release from the spent fuel.

Pressurized water reactor (PWR) and boiling water reactor (BWR) are the most popular light water reactor. The Daya Bay Nuclear Power Station (大亞灣核電站) near Hong Kong is a PWR which has a radioactive primary loop to heat up water that transfers heat to a secondary loop through a steam generator. The steam generated in the non-radioactive secondary loop drives turbine-generators to produce electricity.

The reactors at Fukushima I are BWR. Unlike PWRs, the reactor pressure vessel (RPV) of BWRs directly makes steam that drives the turbine generators, as illustrated in Figure 1. After driving the turbine, the expanded steam is condensed and pumped back into the RPV through feedwater pumps. Because the steam driving the turbines comes directly from the reactor core, the turbine system is slightly radioactive and must be shielded during normal operation. However, because the water used in BWRs is extremely pure with no contaminants to absorb radiation, most of the radioactivity in the water is very short-lived (mostly N-16, with a 7-second half-life). The turbine hall is accessible soon after the reactor is shut down for maintenance. The increased cost related to operation and maintenance of BWRs tends to be balanced out by the savings from a lower initial capital investment due to the simpler design and greater thermal efficiency.

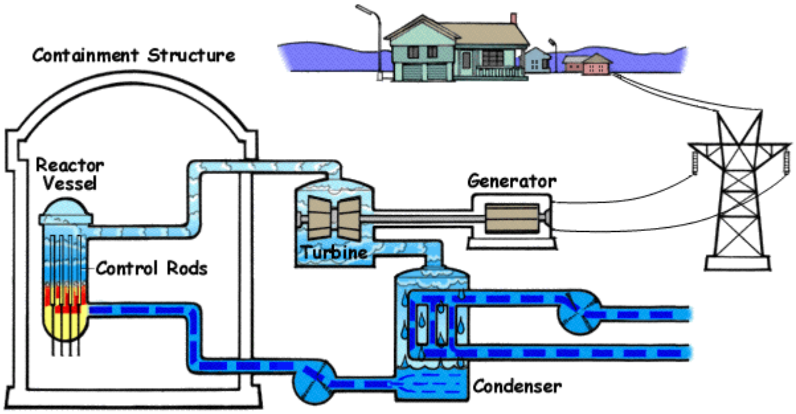

Figure 1 – The Schematic of a Typical BWR

Generation Gap

Although all six units at Fukushima I are BWRs, they do not share an identical design. The oldest , unit 1, is a BWR-3 (a third generation BWR), while Units 2 to 5 are BWR-4 with Unit 6 is a more modern BWR-5.

While all BWR-1s had been decommissioned, BWR-2 and the subsequent generations of BWRs were designed to have a more efficient core with redundant emergency core cooling system (ECCS) and a pressure-suppression-type pool. An ECCS includes high pressure and low pressure injection systems to provide cooling for removal of residual heat, which is generated from the nuclear fuel even the nuclear reaction has stopped and the plant is in shutdown mode. Heat from spent fuel plays a major role in the incident at Fukushima I.

Internal jet pumps driving the core flow inside the RPV were introduced in BWR-3 to reduce the number of recirculation loops. The reduction in pipings, valves, pumps, and nozzles helps improve overall reliability. The BWR-4 and BWR-5 designs further improved ECCS and reliability, and provided higher core power densities.

Which Mark is it?

The containment structure for BWR-1s, designed to be the final barrier to radiological release to the atmosphere, is referred to as Mark I. Since its introduction in the 1960s, Mark I has been criticized for its less than sturdy design. Hence, Mark I has received numerous safety upgrades over the years, and led the introduction of improved Mark II and Mark III designs.

Units 1-5 use Mark I containment structures, similar to the one illustrated in Figure 2. A typical Mark I consists of a rectangular or square reactor building with 1.2–2.4 m of steel-reinforced pre-stressed concrete designed to seal off the reactor from the environment with a slightly negative ambient pressure. Inside the building, there are:

(1) A steel-lined cylindrical drywell, which is surrounded by steel-reinforced concrete, encloses the RPV and recirculation loops.

(2) A steel-lined pressure suppression wetwell (torus) that stores a large body of water used to quench steam from the drywell in case of accident, to limit pressure built-up.

(3) A secondary containment, which surrounds the primary containment (drywell and the torus) and houses the spent fuel pool and ECCS.

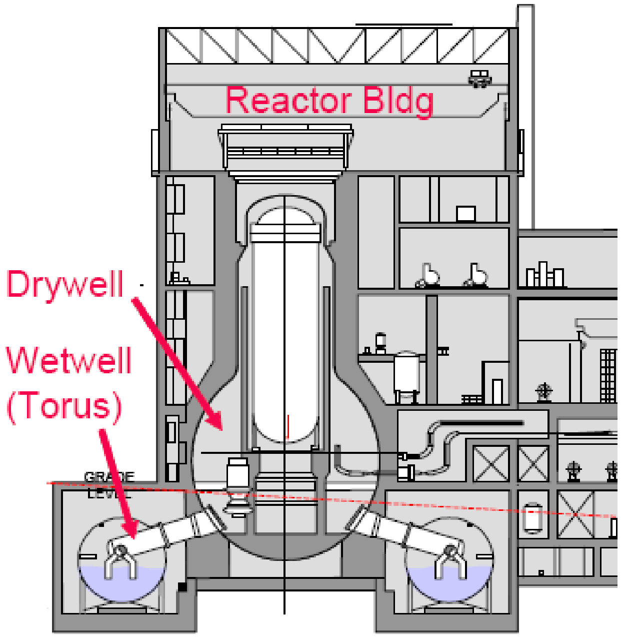

Figure 2 – Typical BWR Mark I Containment with Steel Torus

BWR plants are known to have a lower theoretical core melt risk than PWR plants; however, BWRs' weaker containment design gives a larger containment failure risk. Without a PWR-style large, cylindrical thick concrete containment with a dome-shaped top housing the RPV and steam generators, a BWR reactor building is more vulnerable to explosion and the release of radiation. However, BWRs do have their advantages: a lower probability of pipe rupture that causes loss of coolant accidents (LOCA) due to the simpler, lower pressure design. BWR plants incorporate unique functionally redundant ECCS with high pressure and low pressure coolant injection systems and a reactor core isolation cooling (RCIC) system to remove residual heat from the nuclear fuel.

Double Jeopardy

Nuclear power plants are designed with multiple safety bariers so that earthquakes and accidents within design criteria should not jeopardise safety. Fukushima I was designed for peak ground acceleration (PGA) of 0.18g and is protected by a seawall to withstand a 5-m flood. All units were inspected after the magnitude 7.7 Miyagi earthquake of 1978 with the PGA measured 0.125g for 30 seconds; no damage to the critical reactor systems was discovered. The 2011 Sendai earthquake was initially reported to have a PGA of 0.35g near the epicentre. While the PGA at Fukushima I is not available at the time of writing, the magnitude of Sendai earthquake most likely exceeded what it was designed to withstand. The 13-m high tsunami certainly did.

While loss of coolant, fires, floods, and loss of offsite power are all individually considered to be major risk contributors to reactors, Fukushima I experienced all of these within hours of the Sendai earthquake and tsunami, which act as common failure modes. While units 4-6 had been shut down prior to the earthquake for planned maintenance, units 1-3 were automatically shut down after the earthquake per design.

However, the subsequent tsunami, which was beyond what was anticipated by the design scenarios, knocked out emergency generators needed to run pumps to provide residual heat cooling. Loss of external power and depletion of back-up batteries resulted in total loss of pumping to replenish the coolant. The matter was complicated by the inability to bring repair materials and assistance due to the collapse of infrastructure, compounded with numerous magnitude 6 aftershocks. All these were too much for the 40 years old Fukushima I.

In the days following 11 March 2011, explosions and fire damaged the upper reactor building of units 1-4. With the depletion of water to cool spent fuel at upper reactor buildings, the exposed spent fuel became the primary source of radioactive contamination. Seawater was injected to cool the containment but it is not clear whether the spent fuel pools were intact. Restoring external power, ECCS and pump network to spent fuel pools would be the priority task for avoiding further release of nuclear contaminants.

Learning from the Past

After the Three Mile Island accident, the nuclear industry saw marked interests in developing reactors with passive safety features with less dependence on operator interventions during accidents to minimise human errors. The Chernobyl accident bought significant changes to not only reactor safety but also attention to safety culture across all industries. The Fukushima accident will reshape the nuclear world by driving it to look beyond design basis events and common mode catastrophes. Some older nuclear plants in earthquake prone regions may even face premature shut down as a result of this event.

The designs of the latest advanced reactors focus on passive natural circulation, better reliability, and more efficient use of fuel materials. Risk reduction through these efforts may turn the unfortunate Fukushima event into a positive step forward for the nuclear option.

About the Author: Ir Dr Vincent Ho is the Past Chairman of Safety Specialists Committee and the contributor to the Safety Corner. Dr Ho received his PhD in Nuclear Engineering from the University of California, Los Angeles, specialising in risk management and safety.

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