AN INTRODUCTION TO BOILING WATER REACTORS
AND
THE NUCLEAR EVENT
IN
FUKUSHIMA, JAPAN

1. INTRODUCTION

This document is part of a large group of white papers prepared by the Senior Engineer of **AscenTrust** for the primary stakeholders of the **SMR (Small Modular Reactor)** project. This document is a compilation of information contained in white papers undertaken by the Senior Engineer covering aspects of the production of electrical power with the use of Nuclear Power. The objective of these white papers was to provide a knowledge base consisting of factual, up-to-date information on aspects of nuclear power needed to make the safety case for the existing nuclear power production fleet in the U.S.

The method used is systematic and selective collection, condensation, and presentation of existing information for public dissemination and for the use by generalist as well as by the technical staff associated with our stakeholders. These papers are not intended to provide design guidelines but rather as background sources to support detailed or specialized analyses and reviews of our **NTSMR (Nuclear Technology Small Modular Reactor)** nuclear power project.

The scope of this analysis includes some of the topics and issues deemed of paramount importance to the funding and licensing of the **SMR Project.**. Prime among these issues is the safety case for small Modular reactors. This issue, together with those covered in the other papers, was in fact responsible for the near a halt in the development of nuclear power in most countries.

Since **AscenTrust, LLC. (The Company)** is now actively involved in the funding of the **SMR Prototype Project,** we are engaged in discussions with an Investment Group and several countries that have a sizeable nuclear component in their power system. This document was undertaken to familiarize the staff of our stakeholders with the scientific facts, and provide an answer to the questions which are often posed:

1. How safe is the operation of your Nuclear Power Technology?
2. What about Three Mile Island and Chernobyl ?
3. What happened in Japan
4. How does your reactor technology mitigate the **LOCA** (Loss of Coolant Accident)
5. What are you intending to do about proliferation?
6. How will your technology address the problems of terrorism?
7. What is your solution to the Nuclear waste problem?

This paper was written specifically to address the third question:

What happened in Fukushima Japan.

The paper begins with an introduction to the type of **Light Water reactor technology:**

- Boiling Water Reactors

Which was used by the Japanese at the plant in Fukushima Japan.

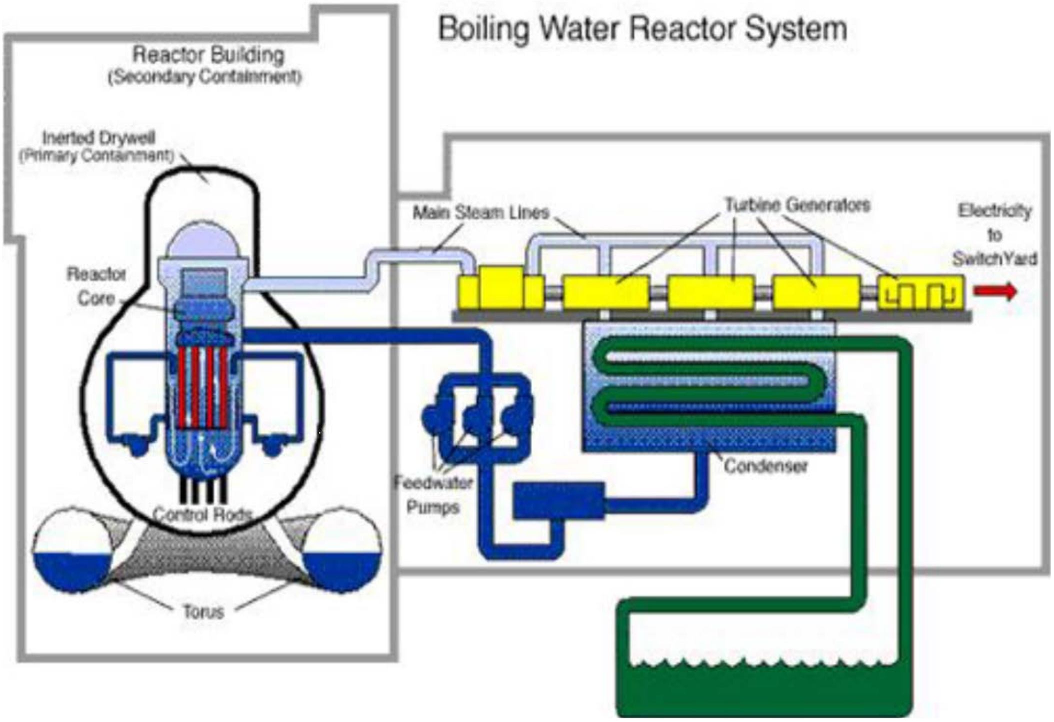
Two major accidents have occurred in the history of commercial nuclear power before the events at Fukushima: **Three Mile Island** (TMI) and **Chernobyl**. In the first accident which occurred in 1979, the reactor core suffered major damage and enormous loss of investment and cleanup cost ensued. However, the releases of radioactivity to the environment were minor.

2. BOILING WATER REACTOR

2.1. INTRODUCTION

The **Boiling Water Reactor (BWR)** uses demineralized water (light water) as a coolant and neutron moderator. Heat is produced by nuclear fission in the reactor core, and this causes the cooling water to boil, producing steam. The steam is directly used to drive a turbine, after which it is cooled in a condenser and converted back to liquid water. This water is then returned to the reactor core, completing the loop. The cooling water is maintained at about 75 atm (7.6 MPa, 1000-1100 psi) so that it boils in the core at about 285°C (550°F). In comparison, there is no significant boiling allowed in a **PWR** because of the high pressure maintained in its primary loop - approximately 158 atm (16 MPa, 2300 psi). The recent nuclear event in Fukushima, Japan occurred in a General Electric **MARK I NUCLEAR POWER PLANT.**

BOILING WATER REACTOR SCHEMATIC



2.2. BOILING WATER REACTOR OPERATIONS

1. The reactor core transfers the fission energy, primarily kinetic energy created by recoil of the fission fragments in the fuel rods into thermal energy of the water which is both the moderator and the cooling agent in a Light Water Reactor.

2. A steam-water mixture is produced when very pure water (reactor coolant) move upward through the core absorbing heat.
3. The steam-water mixture leaves the top of the core and enters the two stages of water seperation where the water droplets are removed and the steam is dried before entering the steam lines.
4. The steam line directs the steam to the main turbine causing it to turn the turbine which is connected to the generator to create electrical power.
5. The unused steam is condensed into water.
6. The resulting water is pumped out of the condenser with a series of pumps, reheated and pumped back to the reactor vessel.
7. The reactor's core contains fuel assemblies which are cooled by water, which is force-circulated by electrically powered pumps.
8. Emergency cooling water is supplied by other water sources which can be powered by onsite diesel generators.

2.3. NUCLEAR STEAM SUPPLY SYSTEM

Steam exiting from the turbine flows into condensers located underneath the low pressure turbines where the steam is cooled and returned to the liquid state (condensate). The condensate is then pumped through feedwater heaters that raise its temperature using extraction steam from various turbine stages. Feedwater from the feedwater heaters enters the reactor pressure vessel (RPV) through nozzles high on the vessel, well above the top of the nuclear fuel assemblies (these nuclear fuel assemblies constitute the "core") but below the water level.

The feedwater enters into the downcomer region and combines with water exiting the water separators. The feedwater subcools the saturated water from the steam separators. This water now flows down the downcomer region, which is separated from the core by a tall shroud. The water then goes through either jet pumps or internal recirculation pumps that provide additional pumping power (hydraulic head). The water now makes a 180 degree turn and moves up through the lower core plate into the nuclear core where the fuel elements heat the water. Water exiting the fuel channels at the top guide is about 12 to 15% saturated steam (by mass), typical core flow may be 45,000,000 kg/hr (100,000,000 lb/hr) with 6,500,000 kg/hr (14,500,000 lb/hr) steam flow. However, core-average void fraction is a significantly higher fraction (~40%). These sort of values may be found in each plant's publicly available Technical Specifications, Final Safety Analysis Report, or Core Operating Limits Report.

The heating from the core creates a thermal head that assists the recirculation pumps in recirculating the water inside of the RPV. A BWR can be designed with no recirculation pumps and rely entirely on the thermal head to recirculate the water inside of the RPV. The forced recirculation head from the recirculation pumps is very useful in controlling power, however. The thermal power level is easily varied by simply increasing or decreasing the forced recirculation flow through the recirculation pumps.

The two phase fluid (water and steam) above the core enters the riser area, which is the upper region contained inside of the shroud. At the top of the riser area is the water separator. By swirling the two phase flow in cyclone separators, the steam is separated and rises upwards towards the steam dryer while the water remains behind and flows horizontally out into the downcomer region. In the downcomer region, it combines with the feedwater flow and the cycle repeats.

The saturated steam that rises above the separator is dried by a chevron dryer structure. The steam then exits the RPV through four main steam lines and goes to the turbine.

2.4. CONTROL SYSTEM

Reactor power is controlled via two methods: by inserting or withdrawing control rods and by changing the water flow through the reactor core. Positioning (withdrawing or inserting) control rods is the normal method for controlling power when starting up a BWR. As control rods are withdrawn, neutron absorption decreases in the control material and increases in the fuel, so reactor power increases. As control rods are inserted, neutron absorption increases in the control material and decreases in the fuel, so reactor power decreases. Some early BWRs and the proposed ESBWR (Economic Simplified BWR made by General Electric Hitachi) designs use only natural circulation with control rod positioning to control power from zero to 100% because they do not have reactor recirculation systems. Fine reactivity adjustment would be accomplished by modulating the recirculation flow of the reactor vessel.

Changing (increasing or decreasing) the flow of water through the core is the normal and convenient method for controlling power. When operating on the so-called "100% rod line," power may be varied from approximately 30% to 100% of rated power by changing the reactor recirculation system flow by varying the speed of the recirculation pumps. As flow of water through the core is increased, steam bubbles ("voids") are more quickly removed from the core, the amount of liquid water in the core increases, neutron moderation increases, more neutrons are slowed down to be absorbed by the fuel, and reactor power increases. As flow of water through the core is decreased, steam voids remain longer in the core, the amount of liquid water in the core decreases, neutron moderation decreases, fewer neutrons are slowed down to be absorbed by the fuel, and reactor power decreases.

2.5. POWER PRODUCTION CAPACITY

2.5.1. **Steam turbines:** Steam produced in the reactor core passes through steam separators and dryer plates above the core and then directly to the turbine, which is part of the reactor circuit. Because the water around the core of a reactor is always contaminated with traces of radionuclides, the turbine must be shielded during normal operation, and radiological protection must be provided during maintenance. The increased cost related to operation and maintenance of a BWR tends to balance the savings due to the simpler design and greater thermal efficiency of a BWR when compared with a PWR.

2.5.2. **Size**: A modern BWR fuel assembly comprises 74 to 100 fuel rods, and there are up to approximately 800 assemblies in a reactor core, holding up to approximately 140 tons of uranium.

2.6. PLANT AND REACTOR SAFETY SYSTEMS

2.6.1. Safety Systems: Like the pressurized water reactor, the BWR reactor core continues to produce heat from radioactive decay after the fission reactions have stopped, making a core damage incident possible in the event that all safety systems have failed and the core does not receive coolant. Also like the pressurized water reactor, a boiling water reactor has a negative void coefficient, that is, the neutron (and the thermal) output of the reactor decreases as the proportion of steam to liquid water increases inside the reactor. However, unlike a pressurized water reactor which contains no steam in the reactor core, a sudden increase in BWR steam pressure will result in a sudden decrease in the proportion of steam to liquid water inside the reactor. The increased ratio of water to steam will lead to increased neutron moderation, which in turn will cause an increase in the power output of the reactor. This type of event is referred to as a "pressure transient".

The BWR is specifically designed to respond to pressure transients, having a "pressure suppression" type of design which vents overpressure using safety relief valves to below the surface of a pool of liquid water within the containment, known as the "wetwell" or "torus". There are 11 safety overpressure relief valves on BWR/1-BWR/6 models (7 of which are part of the ADS) and 18 safety overpressure relief valves on ABWR models, only a few of which have to function to stop the pressure rise of a transient.

Because of this effect in BWRs, operating components and safety systems are designed to ensure that no credible scenario can cause a pressure and power increase that exceeds the systems' capability to quickly shutdown the reactor before damage to the fuel or to components containing the reactor coolant can occur. In the limiting case of an ATWS derangement, high neutron power levels (~ 200%) can occur for less than a second, after which actuation of SRVs will cause the pressure to rapidly drop off. Neutronic power will fall to far below nominal power (the range of 30% with the cessation of circulation, and thus, void clearance) even before ARI or SLCS actuation occurs. Thermal power will be barely affected.

2.6.2. Reactor Core Isolation Cooling System (RCIC): The Reactor Core Isolation Cooling System is not a safety-related system proper, but is included because it can help cool the reactor in the event of a contingency, and it has additional functionality in advanced versions of the BWR. RCIC is designed to remove the residual heat of the fuel from the reactor once it has been shut down. It injects approximately 2,000 L/min (600 gpm) into the reactor core for this purpose, at high pressure. It also takes less time to start than the HPCI system, approximately 5 seconds from an initiating signal

2.6.3. Containment system: The ultimate safety system inside and outside of every BWR are the numerous levels of physical shielding that both protect the reactor from the outside world and protect the outside world from the reactor.

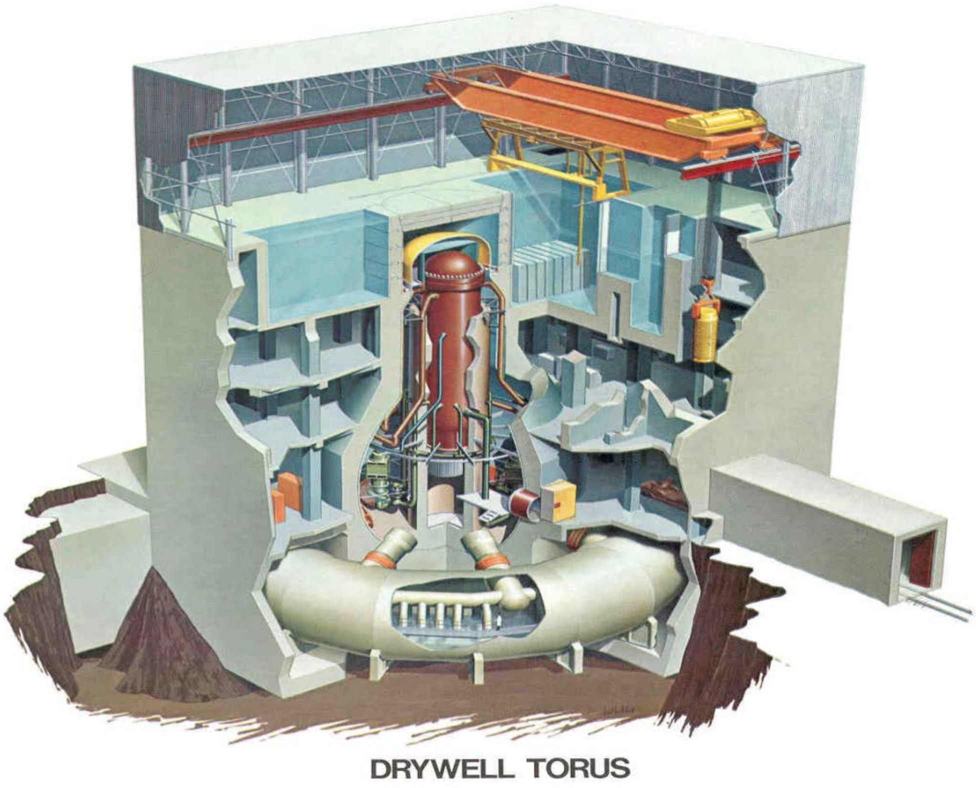
There are five levels of shielding:

1. The fuel rods inside the reactor pressure vessel are coated in thick Zircalloy shielding;
2. The reactor pressure vessel itself is manufactured out of 6 inch thick steel, with extremely temperature, vibration, and corrosion resistant surgical stainless steel grade grade 316L plate on both the inside and outside;
3. The primary containment structure is made of steel 1 inch thick;
4. The secondary containment structure is made of steel-reinforced, pre-stressed concrete 1.2 - 2.4 meters (4 – 8 feet) thick.
5. The reactor building (the shield wall/missile shield) is also made of steel-reinforced, pre-stressed concrete .3 m to 1 m (1 – 3 feet) thick.

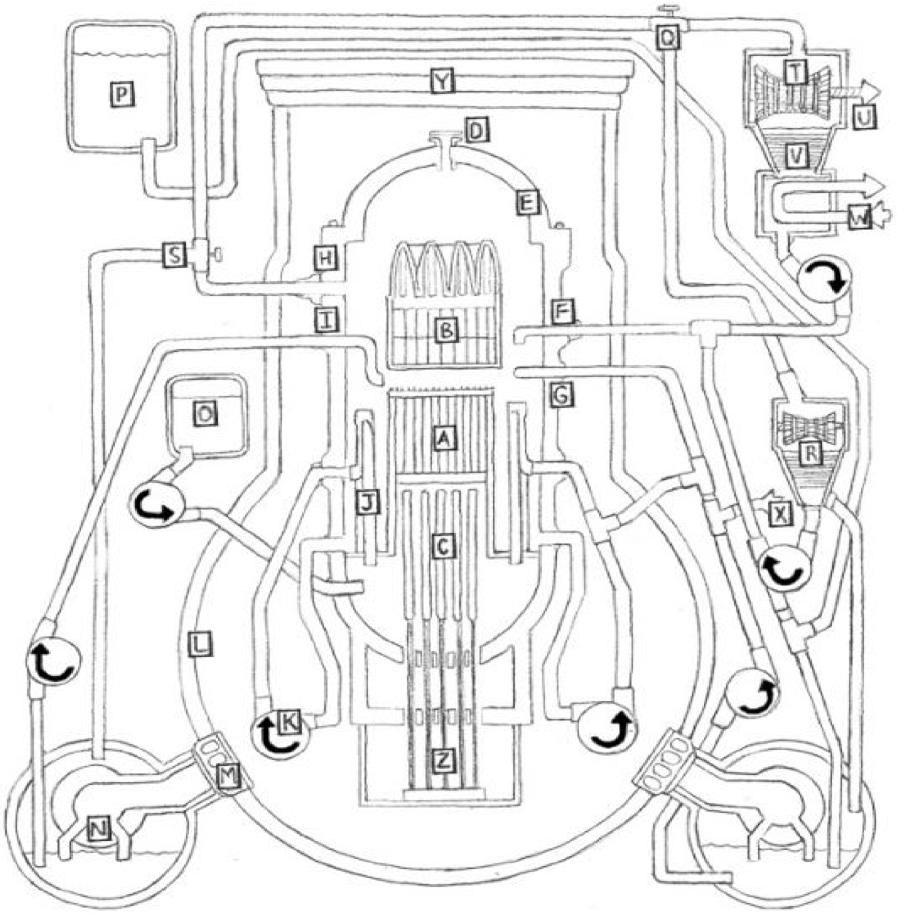
If every possible measure standing between safe operation and core damage fails, the containment can be sealed indefinitely, and it will prevent any substantial release of radiation to the environment from occurring in nearly any circumstance.

2.7. THE EVENT IN THE GE-MARK I REACTOR AT FUKUSHIMA, JAPAN

ISOMETRIC VIEW OF GE-MARK I NUCLEAR POWER PLANT



SCHEMATIC OF GE-MARK I REACTOR AT FUKUSHIMA, JAPAN



Mark I Reactor Components

A.	Uranium fuel rods
B.	Steam Separator and dryer assemblies
C.	Graphite control rods
D.	Vent and head spray
E.	Reactor Vessel
F.	Feedwater inlet
G.	Low pressure coolant injection inlet
H.	Steam Outlet
I.	Core spray inlet
J.	Jet pump
K.	Recirculation pump
L.	Concrete Shell “Drywell”
M.	Venting System
N.	Suppression pool
O.	Boron tank
P.	Condensate storage tank
Q.	High pressure coolant injection system
R.	HCIS turbine
S.	Automatic depressurization system
T.	Main Turbine
U.	Connection to generator
V.	Condenser
W.	Circulating Water
X.	Connection to outside water
Y.	Concrete shield plugs
Z.	Control rod drive

2.7.1. THE NUCLEAR EVENT AT FUKUSHIMA, JAPAN

The earthquake that hit Japan was 5 times more powerful than the worst earthquake the nuclear power plant was designed and built for (the Richter scale works logarithmically; the difference between the 8.2 that the plants were built for and the 8.9 that happened is 5 times, not 0.7). So the first hooray for Japanese engineering, everything held up.

When the earthquake hit with 8.9, the nuclear reactors all went into automatic shutdown. Within seconds after the earthquake started, the control rods had been inserted into the core and nuclear chain reaction of the uranium stopped. When the rods are inserted into the reactor core the turbines are automatically taken off-line. Now, the auxiliary diesel generators need to start and activate the cooling system which has to carry away the residual heat. The residual heat load is about 3% of the heat load under normal operating conditions.

The earthquake destroyed the external power supply of the nuclear reactor. That is one of the most serious accidents for a nuclear power plant, and accordingly, a “plant black out” receives a lot of attention when designing backup systems. The power is needed to keep the coolant pumps working. Since the power plant had been shut down, it cannot produce any electricity by itself any more.

Things were going well for an hour. One set of multiple sets of emergency Diesel power generators kicked in and provided the electricity that was needed. Then the Tsunami came, much bigger than people had expected when building the power plant. The tsunami took out all multiple sets of backup Diesel generators.

When designing a nuclear power plant, engineers follow a philosophy called “Defense of Depth”. That means that you first build everything to withstand the worst catastrophe you can imagine, and then design the plant in such a way that it can still handle one system failure (that you thought could never happen) after the other. A tsunami taking out all backup power in one swift strike is such a scenario. The last line of defense is putting everything into the third containment, that will keep everything, whatever the mess, control rods in our out, core molten or not, inside the reactor.

When the diesel generators were gone, the reactor operators switched to emergency battery power. The batteries were designed as one of the backups to the backups, to provide power for cooling the core for 8 hours. And they did.

Within the 8 hours, another power source had to be found and connected to the power plant. The power grid was down due to the earthquake. The diesel generators were destroyed by the tsunami. So mobile diesel generators were trucked in.

This is where things started to go seriously wrong. The external power generators could not be connected to the power plant (the plugs did not fit). So after the batteries ran out, the residual heat could not be carried away any more.

At this point the plant operators begin to follow emergency procedures that are in place for a “loss of cooling event”. It is again a step along the “Depth of Defense” lines. The power to the cooling systems should never have failed completely, but it did, so they “retreat” to the next line of defense. All of this, however shocking it seems to us, is part of the day-to-day training the operators go through as part of operator training, right through to managing a core meltdown.

It was at this stage that people started to talk about core meltdown. Because at the end of the day, if cooling cannot be restored, the core will eventually melt (after hours or days), and the last line of defense, the core catcher and third containment, would come into play.

But the goal at this stage was to manage the core while it was heating up, and ensure that the first containment (the Zircaloy tubes that contains the nuclear fuel), as well as the second containment remain intact and operational for as long as possible, to give the engineers time to fix the cooling systems.

Because cooling the core is such a big deal, the reactor has a number of cooling systems, each in multiple versions (the reactor water cleanup system, the decay heat removal, the reactor core isolating cooling, the standby liquid cooling system, and the emergency core cooling system). Which one failed when or did not fail is not clear at this point in time.

So imagine a pressure cooker on the stove, heat on low, but on. The operators use whatever cooling system capacity they have to get rid of as much heat as possible, but the pressure starts building up. The priority now is to maintain integrity of the first containment (keep temperature of the fuel rods below 2200°C), as well as the second containment, the pressure cooker. In order to maintain integrity of the pressure cooker (the second containment), the pressure has to be released from time to time. Because the ability to do that in an emergency is so important, the reactor has 11 pressure release valves. The operators now started venting steam from time to time to control the pressure. The temperature at this stage was about 550°C.

This is when the reports about “radiation leakage” starting coming in. The Senior Engineer explained above why venting the steam is theoretically the same as releasing radiation into the environment, but why it was and is not dangerous. The radioactive nitrogen as well as the noble gases do not pose a threat to human health. At some stage during this venting, the explosion occurred. The explosion took place outside of the third containment (our “last line of defense”), and the reactor building. Remember that the reactor building has no function in keeping the radioactivity contained.

It is not entirely clear yet what has happened, but this is the likely scenario: The operators decided to vent the steam from the pressure vessel not directly into the environment, but into the space between the third containment and the reactor building (to give the radioactivity in the steam more time to subside). The problem is that at the high temperatures that the core had reached at this stage, water molecules can “disassociate” into oxygen and hydrogen – an explosive mixture. And it did explode, outside the third containment, damaging the reactor building around.

It was that sort of explosion, but inside the pressure vessel (because it was badly designed and not managed properly by the operators) that lead to the explosion of Chernobyl. This was never a risk at Fukushima. The problem of hydrogen-oxygen formation is one of the most important in the design of a power plant (if you are not Soviet, that is), so the reactor is built and operated in a way it cannot happen inside the containment. It happened outside, which was not intended but a possible scenario and OK, because it did not pose a risk for the containment.

So the pressure was under control, as steam was vented. Now, if you keep boiling your pot, the problem is that the water level will keep falling and falling. The core is covered by several meters of water in order to allow for some time to pass (hours, days) before it gets exposed. Once the rods start to be exposed at the top, the exposed parts will reach the critical temperature of 2200 °C after about 45 minutes. This is when the first containment, the Zircaloy tube, would fail.

And this started to happen. The cooling could not be restored before there was some (very limited, but still) damage to the casing of some of the fuel. The nuclear material itself was still intact, but the surrounding Zircaloy shell had started melting. What happened now is that some of the byproducts of the uranium decay – radioactive Cesium and Iodine –

started to mix with the steam. The big problem, uranium, was still under control, because the uranium oxide rods were good until 3000 °C. It is confirmed that a very small amount of Cesium and Iodine was measured in the steam that was released into the atmosphere.

It seems this was the “go signal” for a major plan B. The small amounts of Cesium that were measured told the operators that the first containment on one of the rods somewhere was about to give. The Plan A had been to restore one of the regular cooling systems to the core. Why that failed is unclear. One plausible explanation is that the tsunami also took away / polluted all the clean water needed for the regular cooling systems.

The water used in the cooling system is very clean, demineralized (like distilled) water. The reason to use pure water is the above mentioned activation by the neutrons from the Uranium: Pure water does not get activated much, so stays practically radioactive-free. Dirt or salt in the water will absorb the neutrons quicker, becoming more radioactive. This has no effect whatsoever on the core – it does not care what it is cooled by. But it makes life more difficult for the operators and mechanics when they have to deal with activated (i.e. slightly radioactive) water.

But Plan A had failed – cooling systems down or additional clean water unavailable – so Plan B came into effect. This is what it looks like happened:

In order to prevent a core meltdown, the operators started to use sea water to cool the core. I am not quite sure if they flooded our pressure cooker with it (the second containment), or if they flooded the third containment, immersing the pressure cooker.

The point is that the nuclear fuel has now been cooled down. Because the chain reaction has been stopped a long time ago, there is only very little residual heat being produced now. The large amount of cooling water that has been used is sufficient to take up that heat. Because it is a lot of water, the core does not produce sufficient heat any more to produce any significant pressure. Also, boric acid has been added to the seawater. Boric acid is “liquid control rod”. Whatever decay is still going on, the Boron will capture the neutrons and further speed up the cooling down of the core.

The plant came close to a core meltdown. Here is the worst-case scenario that was avoided: If the seawater could not have been used for treatment, the operators would have continued to vent the water steam to avoid pressure buildup. The third containment would then have been completely sealed to allow the core meltdown to happen without releasing radioactive material. After the meltdown, there would have been a waiting period for the intermediate radioactive materials to decay inside the reactor, and all radioactive particles to settle on a surface inside the containment. The cooling system would have been restored eventually, and the molten core cooled to a manageable temperature. The containment would have been cleaned up on the inside. Then a messy job of removing the molten core from the containment would have begun, packing the (now solid again) fuel bit by bit into transportation containers to be shipped to processing plants. Depending on the damage, the block of the plant would then either be repaired or dismantled.

2.7.2. COMMENTARY FROM THE SENIOR ENGINEER

- The plant is safe now and will stay safe.
- Japan is looking at an **INES** Level 2 Accident: Nuclear accident with local consequences. That is bad for the company that owns the plant, but not for anyone else.
- Some radiation was released when the pressure vessel was vented. All radioactive isotopes from the activated steam have gone (decayed). A very small amount of Cesium was released, as well as Iodine. If you were sitting on top of the plants' chimney when they were venting, you should probably give up smoking to return to your former life expectancy. The Cesium and Iodine isotopes were carried out to the sea and will never be seen again.
- There was some limited damage to the first containment. That means that some amounts of radioactive Cesium and Iodine will also be released into the cooling water, but no Uranium or other nasty stuff (the Uranium oxide does not "dissolve" in the water). There are facilities for treating the cooling water inside the third containment. The radioactive Cesium and Iodine will be removed there and eventually stored as radioactive waste in terminal storage.
- The seawater used as cooling water will be activated to some degree. Because the control rods are fully inserted, the Uranium chain reaction is not happening. That means the "main" nuclear reaction is not happening, thus not contributing to the activation. The intermediate radioactive materials (Cesium and Iodine) are also almost gone at this stage, because the Uranium decay was stopped a long time ago. This further reduces the activation. The bottom line is that there will be some low level of activation of the seawater, which will also be removed by the treatment facilities.
- The seawater will then be replaced over time with the "normal" cooling water
- The reactor core will then be dismantled and transported to a processing facility, just like during a regular fuel change.
- Fuel rods and the entire plant will be checked for potential damage. This will take about 4-5 years.
- The safety systems on all Japanese plants will be upgraded to withstand a 9.0 earthquake and tsunami (or worse)

As the Senior Engineer of the **SMR Protype Project,** I believe the most significant problem will be a prolonged power shortage. 11 of Japan's 55 nuclear reactors in different plants were shut down and will have to be inspected, directly reducing the nation's nuclear power generating capacity by 20%, with nuclear power accounting for about 30% of the national total power generation capacity. I have not looked into possible consequences for other nuclear plants not directly affected. This will probably be covered by running gas power plants that are usually only used for peak loads to cover some of the base load as well. I am not familiar with Japan 's energy supply chain for oil, gas and coal, and what damage the harbors, refinery, storage and transportation networks have suffered, as well as damage to the national distribution grid. All of these items will increase the cost of energy and lead to higher electricity bill, as well as lead to power shortages during peak demand and reconstruction efforts.

This all is only part of a much bigger picture. Emergency response has to deal with shelter, drinking water, food and medical care, transportation and communication infrastructure, as well as electricity supply. In a world of lean supply chains, we are looking at some major challenges in all of these areas.

Of all the 54 nuclear reactors built prior to the Fukushima nuclear disaster, 43 of them remain operable but only 9 reactors are currently in use. The Ministry of Economy, Trade and Industry said in 2017 that if the country is to meet its obligations under the Paris climate accord, then nuclear energy needs to make up between 20-22% of the nation's portfolio mix. 26 restart applications are now pending with an estimated 12 units to come back in service by 2025 and 18 by 2030.