L2 Newsletter

April 2011 : Issue No: 4

L2 BUSINESS CONSULTING

Initial Analysis of the Fukushima Dai-ichi Nuclear Accident

Welcome

This is our fourth newsletter aimed at our customers and other stakeholders with an interest in our activities and markets. We had planned to issue our normal format newsletter this month but following the tragic events on 11 March 2011 of the Great East Japan earthquake and subsequent tsunami which hit the north east coast of Japan, we have presented here the initial understanding of the events and the lessons learnt from the Fukushima Dai-ichi Nuclear Accident undertaken by one of our Directors, Mark Lyons.

The events which have unfolded at Fukushima Dai-ichi have I'm sure affected everyone in the global nuclear industry. From a personal point of view, this is the worst nuclear plant accident since I started my career in the industry during 1991.

During the weeks that followed the accident I decided to undertake my own analysis of events and this article was formed, focussing on the potential early lessons for confirming and enhancing nuclear safety as a result of Learning from Experience (LfE). Like many individuals and organisations my understanding and knowledge is developing on a continual basis as more information becomes available on the accident itself and the resulting actions and outcomes, hence this article is based upon professional interpretation of publicly accessible information. I do accept that as more information becomes available then some of my observations may change.

In particular the UK nuclear industry awaits the publication of the UK Office of Nuclear Regulation (ONR) independent report on the accident, where ONR have committed to producing an interim report by mid May 2011.

Whilst recognising the extreme natural disaster that took place, it does appear that had greater emphasis been placed on the nuclear safety culture at TEPCO and it's regulators, a number of the common cause failures could have been avoided or at least better recovery plans would have been in place. In particular the lessons learnt from the flooding of the EDF Le Blayais Nuclear Power Plant in France in 1999, seem relevant but do not appear to have been adopted by TEPCO.

Already Governments and Industry are responding to the this event and indeed in Europe, the European Commission has instigated plans to undertake 'Stress Testing' of existing nuclear plants. WENRA (Western European Nuclear Regulators' Association) have recently produced draft high level guidance of what this would entail, which no doubt will be developed and expanded on in the months that follow.

Finally I would like to extend my sympathies to Japan to those who have lost loved ones or their homes. I would also like to pay my respect to the workers at the Fukushima Dai-ichi nuclear power plant who continue to work under arduous conditions to regain full control of the plants.

Mark Lyons

Introduction

On 11 March 2011 at 14:46 Japanese Standard Time (JST) the Great East Japan earthquake, rated at magnitude 9 and subsequent tsunami hit the north east coast of Japan. Sited on this coast is the Fukushima Dai-ichi Nuclear Power Plant, located in the town of Okuma in the Futaba District of Fukushima Prefecture, Japan. The plant consists of six Boiling Water Reactors (BWR). These light water reactors have a combined power of 4.7 GWe, making Fukushima Dai-ichi one of the largest nuclear power stations in the world.

The earthquake and associated tsunami disabled the reactor cooling systems, leading to a loss of control of the plant resulting in explosions, fire and nuclear radiation leaks. This lead to a 30 km evacuation/exclusion zone surrounding the plant. The accident has recently been categorised as a ‘level 7’ event on the International Nuclear Event Scale (INES).

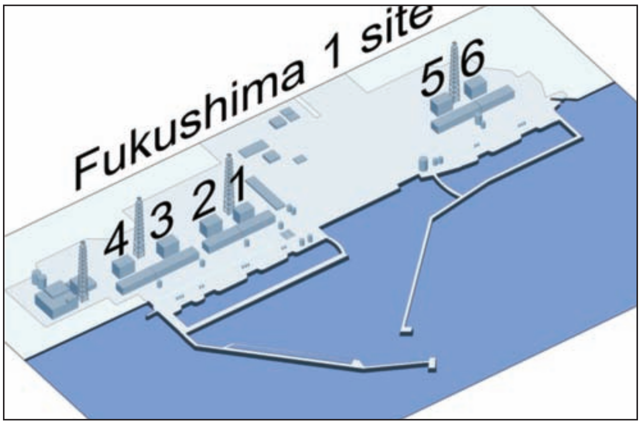
Compared with the tragic loss of life from the tsunami, the direct impact of the events at Fukushima Dai-ichi did not result in any deaths as a result of radiological release however the potential for long term impact of human health is still to be assessed.

This article is focussed on the potential early lessons for confirming and enhancing nuclear safety as a result of Learning from Experience (LfE) from this accident. Like many organisations our understanding and knowledge is developing on a continual basis as more information becomes available on the accident itself and the resulting actions and outcomes, hence this article is based upon professional interpretation of publicly accessible information.

We do accept that as independent factual based information becomes more available then some of our observations may alter. In particular we await the publication of the UK Office of Nuclear Regulation (ONR) independent report on the accident from the HM Chief Inspector of Nuclear Installations, Dr. Mike Weightman.

Compared with the tragic loss of life from the tsunami, the direct impact of the events at Fukushima Dai-ichi did not result in any deaths as a result of radiological release however the potential for long term impact of human health is still to be assessed.

Aerial photograph of the site prior to the accident, Units 1-4 in the foreground, Units 5&6 in the background (© TEPCO)

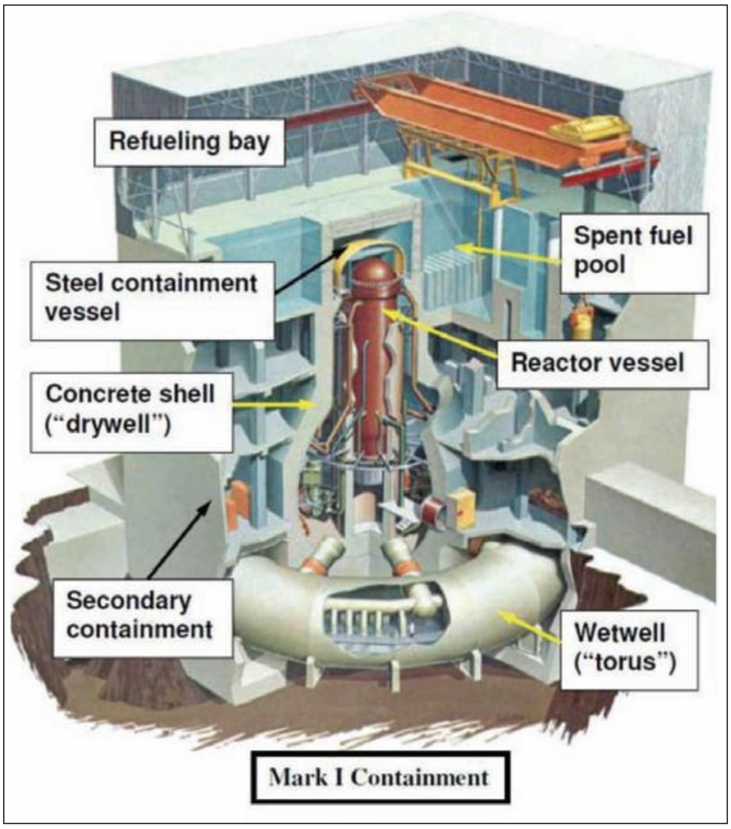


Unit layout and numbering at Fukushima Dai-ichi site (© wikimedia)

Background to BWR Technology

Fukushima Dai-ichi was the first nuclear plant to be constructed and operated entirely by the Tokyo Electric Power Company (TEPCO). Unit 1 is a 460 MWe boiling water reactor (type BWR-3) constructed in July 1967. Units 2-5 are BWR-4 each rated at 784 MWe and Unit 6 is a BWR-5 rated at 1,100 MWe. The units began commercial operations during 1971-1979.

BWR is not a reactor technology we utilise in the UK today. It uses demineralised water as a coolant and neutron moderator. Heat is produced by nuclear fission in the reactor core (which consists of a number of Low Enriched Uranium fuel elements), 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 (ie. a single cycle). The cooling water in the RPV is maintained at about 75 bar so that it boils in the core at about 285 °C.



Simple Geometric of a Generic BWR

The reactors for Units 1, 2, and 6 were supplied by General Electric, those for Units 3 and 5 by Toshiba, and Unit 4 by Hitachi. All six reactors were designed by General Electric. Units 1-5 were built with Mark I type (light bulb torus) containment structures, Unit 6 has a Mark II type (over/under) containment structure.

The purpose of a reactor containment system is to create a barrier against the release of radioactivity generated during nuclear power operations and from certain "design basis" accidents.

The BWR fuel assemblies are about 4 m long, and there are 400 in Unit 1, 548 each in Units 2-5, and 764 in Unit 6. Each assembly has 60 fuel rods containing the low enriched uranium (LEU) oxide fuel within zirconium alloy cladding. Unit 3 has a partial core of mixed oxide (MOX) fuel (32 MOX assemblies, 516 LEU).

The BWR Mark I has a Primary Containment system comprising a free-standing bulb-shaped dry-well of 30 mm steel backed by a reinforced concrete shell, and connected to a torus-shaped wet-well beneath it containing the suppression pool. The dry-well, also known as the Primary Containment Vessel (PCV), contains the reactor pressure vessel (RPV). The water in the suppression pool acts as an energy absorbing medium in the event of an accident. The wet-well is connected to the dry containment (PCV) by a system of vents, which discharge under the suppression pool water in the event of high pressure in the dry containment. The function of the primary containment system is to contain the energy released during any loss-of-coolant accident (LOCA).

During normal operation, the dry containment atmosphere and the wet-well atmosphere are filled with inert nitrogen, and the wet-well water is at ambient temperature.

If a loss of coolant accident (LOCA) occurs, steam flows from the dry-well (PCV) through a set of vent lines and pipes into the suppression pool, where the steam is condensed. Steam can also be released from the reactor vessel through the safety relief valves and associated piping directly into the suppression pool. Steam will be condensed in the wet-well, but hydrogen and noble gases are not condensable and will pressurise the system, as will steam if the wet-well water is boiling. In this case emergency systems will activate to cool the wet-well. Excess pressure from the wet-well can be vented through the 120 m emission stack via a hardened pipe or into the secondary containment above the reactor service floor of the building. If there has been fuel damage, vented gases will include noble gases (krypton & xenon), iodine and caesium, the latter being scrubbed in some scenarios. Less volatile elements in any fission product release will plate out in the containment. The secondary containment houses the emergency core cooling systems and the used nuclear fuel pool. It is not designed to contain high pressure.

The primary cooling circuit of the BWR takes steam from above the core, in the reactor pressure vessel, to the turbine in an adjacent building. After driving the turbines it is condensed and the water is returned to the reactor pressure vessel. There are also two powerful jet-pump recirculation systems forcing water down around the reactor core. When the reactor is shut down, the steam in the main circuit is diverted via a bypass line directly to the condensers, and the heat is deposited there, to the sea. In both situations a steam driven turbine drives the pumps, but condenser function depends on large electrically driven pumps which are not backed up by the diesel generators.

In shutdown mode, the Residual Heat Removal (RHR) system then operates in a secondary circuit (RHR is connected into the two jet-pump recirculation circuits), driven by smaller electric pumps, and circulates water from the rector pressure vessel to RHR heat exchangers which dump the heat to the sea. There is also a Reactor Core Isolation Cooling (RCIC) actuated automatically which can provide make-up water to the reactor vessel (without any heat removal circuit). It is driven by a small steam turbine using steam from decay heat, injecting water from a condensate storage tank or the suppression pool and controlled by the DC battery system.

The Emergency Core Cooling System (ECCS) is a further back-up for loss of coolant. It has high-pressure and low-pressure elements. The high pressure coolant injection (HPCI) system has pumps powered by steam turbines which are designed to work over a wide pressure range. The HPCI draws water from the large torus suppression chamber beneath the reactor as well as a water storage tank. For lower pressures, there is also a Low-Pressure Coolant Injection (LPCI) mode through the RHR system but utilising the suppression pool water, and a core spray system, all electrically-driven. All ECCS sub-systems require some power to operate valves etc, and the battery back-up to generators may provide this.

Beyond these original systems, TEPCO in 1990's installed provision for water injection via the fire extinguisher system through the RHR system (injecting via the jet-pump nozzles) as part of it Severe Accident Management (SAM) countermeasures.

Fukushima Dai-ichi Nuclear Accident Progression

Below is a summary of the timeline for Unit 1 as an example of how and why the accident occurred. A similar series of event happened to varying degrees to Units 1-4 with the exception that in the case of Unit 2, there appears to have been a hydrogen explosion in the wet-well (Note: all time shown are JST).

11 March 2011 14:46	Earthquake hits, sensors detect this and all operating reactors SCRAM control rods. Power generation due to fission of uranium stops, sub-critical state. Heat generation due to radioactive decay of fission products is at around 6% of normal levels immediately after the SCRAM and at around 1% after 24 hours. **Containment Isolation** • Closing of all non-safety related Penetrations of the containment • Cuts off Machine hall • A large early release of fission products is highly unlikely at this stage. Earthquake leads to loss of off-site power (A/C). Diesel Generators (DG) start - Emergency Core cooling systems are supplied from the DG. **Plant is in a stable safe state.**
11 March 2011 15:41	**Tsunami hits the plant** • Plant Design for Tsunami height of up to 5.7m • Actual Tsunami height as it hits the plant is now believed to be 14m. This leads to flooding of Diesel Generators and Essential Service Water Building cooling the generators. Significant damage to buildings and plant on the site. **Station Blackout** • Common cause failure of the power supply • Only Batteries are still available • Failure of all but one Emergency Core Cooling Systems • No restoration of off-site power possible, delays in obtaining and connecting portable generators **Reactor Core Isolation Pump is still available** • Steam from the Reactor drives a Turbine • Steam gets condensed in the Wet-Well • Turbine drives a Pump • Water from the Wet-Well gets pumped in Reactor • Battery power is still available As there is no heat removal from the building, the Core Isolation Pump cannot work indefinitely
11 March 2011 16:36	**The batteries providing essential power in Unit 1 fail** Decay Heat still produces steam in Reactor Pressure Vessel (RPV) pressure rising. Opening the steam relieve valves and discharging steam into the Wet-Well in Unit 1. Descending of the cooling liquid level in the RPV, starts to expose the core in Unit 1. State of nuclear emergency was declared (Fukushima Dai-ichi NPS).
12 March 2011	The decreasing water level in the RPV leads to a continued uncovering of the fuel core. Hydrogen gas is generated due to the Zirconium-Water reaction. Highly likely that the fuel rods have extensive damage as fuel temperature will have exceeded 1000 oC. Around 3/4 of the core exposed. Fuel cladding starts to exceed 1200 °C. Zirconium in the cladding starts to burn under steam atmosphere via the reaction: $\mathbf{Zr + 2H_2O \rightarrow ZrO_2 + 2H_2}$ Exothermal reaction further heats the core and pressurises it. Hydrogen starts to escape from wet-well into dry-well. During the damage to the fuel rods there is a release of fission products and noble gases including Xenon, Caesium, Strontium, Iodine… It is expected that the majority of Uranium and Plutonium remain in fuel in the core. Fission products condensate to airborne aerosols.

12 March 2011 05:30	At Unit 1, unusual increase of PCV pressure results in decision taken to start to vent contents to secondary containment.
12 March 2011 10:09	TEPCO confirms that a small amount of gas has been released into the air to release pressure in Unit 1
12 March 2011 14:30	Start of depressurization (venting) of Unit 1 of PCV to protect primary containment from failure. The depressurisation of the containment removes energy from the reactor and was the last course of action that was possible. However it results in a release of fission products from the damaged fuel. It does however release the hydrogen gas that has built up.
12 March 2011 15:36	The gas that has been released into the reactor service floor and as hydrogen is flammable (4 vol% in air + spark) it eventually ignites and an explosion occurs, destroying the majority of the reactor service floor structures (they provide weather proof enclosure only ie. no safety function). The reinforced concrete reactor building seems undamaged from the blast but it does cause debris around the reactor service floor, the area surrounding the reactor building and probably damages instrumentation & control systems. The release of radioactivity lead to very high radiation levels adjacent to the plant.
12 March 2011 20:20	Seawater and boric acid was injected to the Containment Vessel via the Fire Extinguishing System Line.
17 March 2011	TEPCO begins to drop water onto the units from helicopters to try and increase water levels in the containments and spent fuel ponds
20 March 2011	Restoration of external power to Unit 1
22 March 2011	Seawater injection through feed water line started in addition to fire extinguish water line
24 March 2011	Lights in the main control room of unit 1 becomes available
25 March 2011	Freshwater injection to the reactor begins
29 March 2011	Switched to the water injection to the core using a temporary motor operated pump
31 March 2011	Freshwater is being injected into the RPV

The current status of the units on site moves each day but a simple statement would be that:

- There is believed to be some core damage in Unit 1,2 & 3
- Significant reactor building damage due to various explosions across Unit 1-4
- Reactor Pressure Vessels flooded in all Units with mobile pumps
- Containment in Unit 1 is flooded
- Major release of radioactivity from a possible rupture in the wet-well in Unit 2

In addition to the reactor issues on 15 March 2011, Unit 4 spent fuel stored in cooling pond adjacent to the reactor service floor appeared to cause an explosion then fire occurred and was extinguished. There has been continuing concerns that the spent fuel pond on the Units had lost cooling water via a range of potential mechanisms. Clearly a loss of water acting as both coolant and shielding media could lead to an in air nuclear fuel accident without the benefit of the containment structures of the reactor. TEPCO has initially maintained external emergency cooling of the spent fuel ponds via long reach water injection devices, then by more conventional means as access to the reactors has been regained.

Outside the site, during and after the accident there has been wide scale evacuation of the public and varying radiological issues relating to the fission products and noble gases released. These have been carried / distributed by the wind, decreasing dose with time. There has been destruction of crops and dairy products and various control measures placed on food consumption of certain items though some of these are now being lifted. The most significant radionuclides released have thankfully short half lives.

The main group of people exposed to higher doses are the plant and emergency personnel associated with the on-going recovery of the Reactor Units, the majority of which are under 250 mSv, though around six personnel have received doses exceeding this emergency limit.

Unit 1 foreground, Unit 2 relatively undamaged structures, Units 3 and 4 background similar damage to Unit 1 (© TEPCO)

Unit 1 showing damage to secondary structures following hydrogen explosion on reactor service floor (© TEPCO)

Damage at Fukushima Dai-ichi site following the tsunami (© TEPCO)

Lessons Learnt from Previous Nuclear Plant Flooding

A recent and closer to the UK incident occurred in 1999 at the EDF Le Blayais Nuclear Power Plant in France on the Bay of Biscay which resulted in a partial flooding of the nuclear plant. The power plant has 4 nuclear reactors of Pressurised Water Technology (PWR), each producing 951 MWe.

On evening of 27 December 1999, a combination of the incoming tide and high winds overwhelmed the sea walls at the plant and causing parts of the plant to be flooded. The event resulted in the loss of the plant's off-site power supply and knocked out several safety-related backup systems, resulting in a 'level 2' event on the International Nuclear Event Scale (INES).

At the time, units 1, 2 and 4 were at full power, while unit 3 was shut down for refuelling. The operation of units 1 and 2 were affected by flood damage to a number of water pumps and distribution panels, all four units lost their 225kV power supplies, while units 2 and 4 also lost their 400kV power supplies. Diesel backup generators were employed to maintain power to plants 2 and 4 until the 400kV supply was restored. Over the following days an estimated 90,000 m3 of water was pumped out of the flooded buildings

The key issues identified by the incident are summarised below:

Flooding hazards	Severe storm driven waves coinciding with high estuary level exceeded the worst case design basis scenario
Protective measures	• Insufficient height and inadequate shape of the dykes • Insufficient protection of the underground rooms containing safety equipment • Difficulty to detect water in affected rooms • Inadequate warning system • All 4 units concerned, on-site organizational difficulties
Flooding effects on the NPP's support functions and surroundings	Severe storm driven waves coinciding with high estuary level exceeded the worst case design basis scenario

EDF undertook a comprehensive review of the flood risks and produced a series of lessons learnt and management action plans, summarised below:

Flooding Hazards	• Identification of all phenomena, which can result in hazards a flood at any of the 19 French NPP including a re-assessment of flood hazards / impacts at each site
Protective measures	• Identification of equipment to be protected • Review of the existing protective measures (structures, devices, procedures, organization) • Modifications or improvements where required
Flooding effects on the NPP's support functions and surroundings	• Specific Flood procedures developed as necessary • Analysis of the risks: site inaccessibility, loss of off-site power supplies, heat sink behaviour, communications… • Means defined to avoid them or to cope with them

Whilst this incident did not result in the level of accident seen at Fukushima Dai-ichi, some of the common themes are evident. What is more concerning from a nuclear safety culture perspective is that the lessons from this incident in France where widely publicised but a number of them appear not have been adopted by TEPCO.

Initial Lessons Learnt from Fukushima Dai-ichi Nuclear Accident

We have summarised below a number of observations which we believe are pertinent to this accident, these are in no order of importance or priority:

- Potential for a nuclear site to be isolated for much longer than was previously expected. This places greater demands on site based infrastructure, resources and consumables. A review and potential revision of emergency management procedures, equipment and resources may be needed.
- Ongoing provision of SQEP (Suitably Qualified and Experience Personnel) human resource over protracted periods to undertake work to control or repair the plants did not appear to have been adequately planned for or delivered. Greater consideration to the resource requirements for different accident scenarios may impact future resource requirements both on and off-site.
- It appeared that TEPCO had not considered the impact of several reactors being simultaneously affected by one accident (ie. greater than current design basis accident) hence physical mitigation measures were inadequate (ie. height of sea wall, loss of surrounding site infrastructure, loss of control rooms, …). A review and potential revision of emergency management procedures and equipment may be needed.
- The tsunami inflicted considerable damage to key plant and systems on site including key emergency safety systems such as the back-up diesel generators which had a catastrophic effect on decay heat cooling. It would appear that greater physical protection of these systems was needed and greater plant redundancy. It would also appear that in the case of site is susceptible to flood risk that there is a need for standby back-up power, via diesel generator and/or battery power, at a suitable elevation above the flood risk level. Consideration should also be given to placing back-up standby power at a suitable distance from the reactor buildings and possible positioning fuel sources separate from these. Whilst recognising the extreme flood outcome placed by the tsunami, it appears that greater understanding of the potential for flood proofing this type of back-up plant in the future is needed.
- Approach to identification and storage of readily available and pre-staged emergency equipment and plant appeared to be inadequate. Given the number of reactors at Fukushima, it would appear logical to have key equipment stored in a physically protected building off-site. There is also clearly a need for critical review of post accident response and management.
- It initially appears that the control rooms did not appear to have more protection to cope with severe accident situations (autonomous power supply, localised back up power supply, shielding, active ventilation,…). We would have also expected that a suitable off-site emergency control room would be available to allow control key plant parameters in the event of abandoning the main reactor control rooms. The need for secondary emergency control rooms should be evaluated.
- The communications during the accident from TEPCO from a public understanding perspective were not adequate and did provide a non-technical person with any degree of understanding of hazard and risk in perspective. Clearly protection of the public is the highest priority for the plant operator, this function requires improvement in terms of planning, utilising multiple routes available and quality of information presented.
- The risk posed by recently removed nuclear fuel from the reactors to the cooling ponds appears to have been under evaluated as it seems the requirements for emergency cooling was under provisioned
- Following the tsunami and the recovery attempts following the plant failures, there has been introduction of significant quantities of water to the site, there appears to have been insufficient protection of the underground rooms containing key safety equipment and plant against water ingress.

Conclusions

This major accident has caused major concerns over the nuclear safety culture within TEPCO and the negative impact to the lives of the residents within the current exclusion zone. It has also had a major economic impact as units 1-4 are now written off at a significant impact to the balance sheet of the business and the reputation of the plant operator plus the wider economic impact to Japan.

Whilst recognising the extreme natural disaster that took place, it does appear that had greater emphasis been placed on the nuclear safety culture at TEPCO a number of the common cause failures could have been avoided or at least better recovery plans would have been in place. The lessons learnt from the flooding of the EDF Le Blayais Nuclear Power Plant in France in 1999 do not appear to have been adopted.

Already in Europe, the European Commission has instigated plans to undertake 'Stress Testing' of existing nuclear plants. WENRA (Western European Nuclear Regulators' Association) have recently produced draft high level guidance of what this would entail. They have defined a 'Stress Test' as a targeted re-assessment of the safety margins of nuclear power plants in the light of the events which occurred at Fukushima: extreme natural events challenging the plant safety functions and leading to a severe accident.

Clearly as the more facts of what happened on the Fukushima Dai-ichi site become available further lessons learnt will be developed which will have international ramifications for the nuclear industry that will be felt for a number of years.

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