Office for Nuclear Regulation

An agency of HSE

Japanese earthquake and tsunami: Implications for the UK Nuclear Industry

Interim Report

HM Chief Inspector of Nuclear Installations

18 May 2011

Executive Summary

Introduction

On the 14 March 2011 the Secretary of State (SoS) for Energy and Climate Change requested HM Chief Inspector of Nuclear Installations to examine the circumstances of the Fukushima accident to see what lessons could be learnt to enhance the safety of the UK nuclear industry. The aim of the report is to identify any implications for the UK nuclear industry, and in doing so co-operate and co-ordinate with international colleagues. The SoS requested that an interim report be produced by the middle of May 2011, with a final report within six months.

This is the interim report (the "HM Chief Inspector's Interim Fukushima Report") referred to above and looks at the initial implications for the UK nuclear industry, mainly the nuclear power sector, that can be learned from the accident that took place at Fukushima. The final report is planned for September 2011 and will cover all nuclear installations.

This report provides some background on radioactive hazards, and how to protect against them, nuclear power technology and the approach to nuclear safety and security in the UK, internationally and in Japan. It also describes how we have taken forward the work so far and how we expect to continue to the final report. The report details who we have liaised with to date and describes the measures we have put in place to provide for external scrutiny of our work.

While not all the circumstances of the accident in Japan are known there is sufficient information to develop initial lessons for the UK. These are discussed together with our preliminary conclusions and recommendations for taking the work forward to the final report.

In taking the findings in this report forward we should recognise that to achieve sustained high standards of nuclear safety we all need to adhere to the principle of *continuous improvement*. This principle is embedded in UK law, where there is a continuing requirement for nuclear designers and operators to reduce risks *so far as is reasonably practicable*. This is underpinned by the requirement for detailed periodic reviews of safety to seek further improvements.

This means that, no matter how high the standards of nuclear design and subsequent operation are, the quest for improvement should never stop. Seeking to learn from events, new knowledge and experience, both nationally and internationally, must be a fundamental feature of the safety culture of the UK nuclear industry.

The UK nuclear regulatory system is largely non-prescriptive. This means that the industry must demonstrate to the regulator that it fully understands the hazards associated with its operations and knows how to control them. The regulator challenges their designs and operations for safety to make sure that their safety provisions are robust and that they minimise any residual risks. So, we expect the industry to take the prime responsibility for learning lessons, rather than relying on the regulator to tell it what to do. What we have done in this report is point out areas for review where lessons may be learnt to further improve safety. But it is for industry to take ultimate responsibility for the safety of their designs and operations.

We anticipate that many of the significant lessons can be identified by the time of the final report. However, with additional detailed information and research some extra insights will arise in the longer term. We intend to monitor closely any such developments as part of continuing to seek improvements in nuclear safety and take these forward with the nuclear industry in line with our normal regulatory approach of challenge, influence and where needed enforcement.

The Earthquake and Tsunami at Fukushima-1

At 2.46pm local time on 11 March 2011 Japan's east coast was hit by a magnitude 9 earthquake - the largest recorded for Japan - and then about an hour later by a tsunami many metres high. This caused considerable damage and loss of life across Japan. There are several nuclear power sites in this area of Japan, including the Fukushima-1 site (Fukushima Dai-ichi) where six Boiling Water Reactors (BWR) are located.

Fukushima-1 Reactors

All the Fukushima-1 reactor units are BWRs designed by General Electric although there are design differences between them. They were designed some 40 years ago. A BWR is a Light Water Reactor (LWR) in which normal (light) water serves both as the reactor coolant and the moderator.

Inside a BWR vessel, a steam water mixture is produced when the reactor coolant moves upward through the fuel elements in the reactor core absorbing heat. The steam/water mixture leaves the top of the core and enters a steam dryer and moisture separator where water droplets are removed before the steam enters the steam line. This directs the steam to the turbine generators where electricity is produced. After passing through the turbines, the steam is condensed in the condenser. All Fukushima's condensers are cooled by sea water passing through the secondary side.

The reactor core is made up of fuel assemblies, control rods and neutron monitoring instruments. All the Fukushima-1 reactor units have two external recirculation loops with variable speed recirculation pumps and jet pumps internal to the reactor vessel.

Fukushima-1 Reactor Units 1 to 5 have a Mark I containment with a light bulb shaped drywell. Reactor unit 6 has a Mark II containment which consists of a steel dome head and concrete wall (post-tensioned or reinforced) standing on a basemat of reinforced concrete. Both Mark I and II containment models have suppression chambers with large volumes of water. The function of these pools is to remove heat if an event occurs in which large quantities of steam are released from the reactor. The suppression pools are often referred to as “Torus” in the Mark I containment models (reactor units 1 to 5). The Mark I torus is a large doughnut shaped steel structure located at the bottom of the drywell surrounding it. The drywell and the torus are designed to withstand the same pressure.

All the Fukushima-1 reactor units have a secondary containment, which surrounds the primary containment (drywell and suppression pool) and houses the emergency core cooling systems. The secondary containment in both the Mark I and Mark II models form part of the Reactor Building. The reactor building above the pilecap is lightweight in nature and not designed to provide a barrier function (it is a weather tight enclosure).

Spent fuel at the Fukushima-1 site is stored in a number of locations:

- Each of the six reactors has its own storage pond. The ponds are located at the top of the reactor building to facilitate fuel handling during refuelling.
- The common pond is a building segregated from the reactors and contains around 6000 spent fuel assemblies.
- Spent fuel is also stored on-site in a dry storage facility that contained nine casks at the time of the event. It is believed that there would typically be 400 assemblies on-site in casks at any particular time.
- Overall, 60 percent of the used fuel on-site is stored in the common pond, 34 percent of the spent fuel was in the reactor ponds and the remaining six percent was in the dry storage facility.

UK Nuclear Reactors

The UK has no BWRs. With the exception of Sizewell B, which is a Pressurised Water Reactor (PWR), all the UK’s nuclear power plants use gas-cooled technology. The first generation (“Magnox”) reactors use natural or slightly enriched uranium with magnesium alloy cladding. The second generation, Advanced Gas-cooled Reactors (AGR), use enriched uranium dioxide fuel with stainless steel cladding. The operating Magnox stations and all of the AGRs use carbon dioxide as the primary coolant and have pre-stressed concrete reactor pressure vessels. They have some fundamental differences to the BWR reactor, e.g. the power density of the reactor core is lower and its thermal capacity is significantly larger, giving much more time for operators to respond to loss of cooling accidents. Under fault conditions, significant quantities of hydrogen are not generated as water is not the coolant.

Sizewell B, which is the most recent nuclear power plant to be built in the UK, is a PWR which became operational in 1995. This reactor uses enriched uranium oxide fuel clad in zircaloy with pressurised water as the coolant. It is one of the most advanced PWRs operating in the world and has improved containment, control of nuclear reactions and hydrogen in fault conditions, and cooling systems compared to many previous designs.

The Accident at Fukushima-1

At the time of the earthquake three reactors (Reactor Units 1 to 3) were operating, with Reactor Unit 4 on refuelling outage and Reactors Units 5 and 6 shut down for maintenance.

When the earthquake struck all three operating reactors at the Fukushima-1 site shut down automatically and shutdown cooling commenced. When the tsunami hit the site all AC electrical power to the cooling systems for the reactor and reactor fuel ponds was lost including that from backup diesel generators. Over the next few days several large explosions and fires occurred as a result of the fuel heating up, the fuel cladding reacting with water and steam and hydrogen being released. In addition, fuel element integrity was lost which led to a significant release of radioactivity into the environment.

The hydrogen explosions caused considerable damage to Reactor Units 1, 3 and 4. Reactor Unit 2 had an internal explosion that appeared to have breached the secondary containment. The site struggled to put cooling water into the reactors and the reactor fuel ponds, by previously untried and unplanned means, for over a week. Electrical supplies were gradually reconnected to the reactor buildings and a degree of control returned. Heavily contaminated water used to cool the reactors and spent fuel ponds collected in uncontained areas of the site and leaked out to sea. Eventually emergency measures were successful in curtailing the uncontrolled discharges.

It was clear that this was a serious nuclear accident. A provisional International Nuclear Event Scale (INES) level 5 was declared in the early stages, but after further analysis of the amount of radioactivity released from the site, the INES rating was increased to provisional level 7.

Early on in the chain of events the Japanese authorities instigated a 3km evacuation zone, then a 10km zone, and later a 20km zone with a 30km sheltering zone along with other countermeasures. Governments across the world watched with concern on how best to protect their citizens in Japan from any major radioactive release that might occur. In the UK the situation was kept under review at the highest level in Government with clear attention to the basic duty of a Government – to protect the citizens of the UK. To assist the UK Government many agencies, government departments and individuals were involved in providing their best technical advice. This was co-ordinated and led by the Government's Chief Scientific Advisor. The Health and Safety Executive's Nuclear Directorate (which became the Office for Nuclear Regulation (ONR) - an Agency of the Health and Safety Executive (HSE) – on 1 April 2011), provided authoritative advice on nuclear safety throughout the crisis.

Relevance to the UK

To establish the relevance to the UK, ONR has taken action on a number of fronts; firstly a dedicated project team has been set up with a technical support team covering aspects of the Fukushima event that are likely to be important in learning lessons. The technical areas include: external hazards; radiological protection, reactor physics, severe accident analysis, human factors, management of safety, civil engineering, electrical engineering, nuclear fuel, spent fuel storage and emergency arrangements.

In addition to ONR's internal team we have actively sought assistance from a wide range of organisations and have issued a broad invitation to anyone able and willing assist.

In order to provide independent technical advice to the Chief Inspector during the production of this report, a wide range of stakeholders were asked to nominate an expert to attend an ONR Technical Advisory Panel (TAP). The TAP has provided valuable input to this interim report and will continue to provide advice as we endeavour to complete our final report for the Secretary of State.

Interim Report Conclusions

The direct causes of the nuclear accident, a magnitude 9 earthquake and the associated 14 metre high tsunami, are far beyond the most extreme natural events that the UK would be expected to experience. We are reassuringly some 1000 miles from the edge of a tectonic plate, where earthquake activity is more common and severe. Design provisions at the Fukushima-1 site appear to only have been made to protect against a 5.7 metre high surge in sea level, and there is a history of large tsunamis hitting this coast of Japan. It is reported that over the 150 years Japan has experienced along its east coast several tsunamis of height greater than six metres, some greater than 20 metres. However, we have been unable to identify the specific history of tsunamis at the Fukushima-1 site.

UK nuclear power plants, both operational and those planned, are of a different design to the BWR reactors at the Fukushima-1 site. In addition, our approach to design basis analysis requires designers and operators to demonstrate that adequate protection is in place for natural events of a very remote nature, based on an extrapolation from the historical record. We then require them to demonstrate that there are no "cliff-edge" effects or that more could not be reasonably done to protect against very remote events. This leads us to conclude that:

> ***Conclusion 1: In considering the direct causes of the Fukushima accident we see no reason for curtailing the operation of nuclear power plants or other nuclear facilities in the UK. Once further work is completed any proposed improvements will be considered and implemented on a case by case basis, in line with our normal regulatory approach.***

Nevertheless, severe events can occur from other causes and learning from events is fundamental to testing the robustness of, and enhancing where needed, the defence in depth provisions. For nuclear sites it is incumbent on both the UK nuclear industry and on us as regulators, to seek to learn lessons and ensure all reasonably practicable steps are taken to enhance nuclear safety.

The UK nuclear power industry has had a good safety record and has taken a pro-active stance in seeking to learn lessons despite the differences in technology employed in the UK to that involved at the Fukushima-1 site. We have been reassured by: the prompt and full response to our requests for assurances on the state of plant protection systems within the first week after the accident; the fact that independently of regulatory interest both the companies operating the UK's nuclear power stations held special board meetings to consider the case for continued operation of the UK's reactors; and by the companies' intention to complete further reviews. We conclude that:

> ***Conclusion 2: In response to the Fukushima accident, the UK nuclear power industry has reacted responsibly and appropriately displaying leadership for safety and a strong safety culture in its response to date.***

When any serious event occurs there are always reasonable questions asked about the regulator. Questions can be about the independence and powers of the regulator, and what confidence people can have in the regulator, although there is nothing to suggest that this was the issue in this accident. In the UK the nuclear regulators operate independently of Government and the industry. In addition, it is the Government's intention to create a more integrated, focused, independent and accountable nuclear regulatory body with greater institutional flexibility to sustain the expert resources it needs to meet the challenges of the future. The proposal is to create ONR as a standalone statutory corporation outside the HSE. The creation of the Nuclear Directorate as an Agency of HSE and its renaming as the Office for Nuclear Regulation on 1 April 2011 is an interim step. Such moves have been praised by a Director General of the International Atomic Energy Agency (IAEA) and should enhance confidence in the UK nuclear regulatory regime. This leads us to conclude that:

> ***Conclusion 3: The Government's intention to take forward proposals to create the Office for Nuclear Regulation, with the post and responsibilities of the Chief Inspector in statute, should enhance confidence in the UK's nuclear regulatory regime to more effectively face the challenges of the future.***

ONR uses its established Safety Assessment Principles (SAP) as the basis for assessments of nuclear plant safety cases and our judgement about the safety of nuclear facilities in the UK. Our work has led us to conclude that:

> ***Conclusion 4: To date, the consideration of the known circumstances of the Fukushima accident has not revealed any gaps in scope or depth of the Safety Assessment Principles for nuclear facilities in the UK.***

More generally, in the course of our examination of the events in Japan, we have not seen any significant defects in the UK's approach to nuclear regulation - i.e. a broadly goal-setting system, underpinned by a flexible and adaptable licensing regime, of which the SAPs form a crucial part. This reinforces the way in which we have been able to develop an effective approach to regulating nuclear new build through a system of Generic Design Assessment (GDA) and specific nuclear site licensing, and construction consents.

> ***Conclusion 5: Our considerations of the events in Japan, and the possible lessons for the UK, has not revealed any significant weaknesses in the UK nuclear licensing regime.***

Questions have been raised as to whether there are any lessons for the existing siting policy and strategy for new reactors in the UK. There are two main aspects in relation to the Japanese accident: location of sites in areas subject to particular onerous natural hazards; and the ability to undertake precautionary counter measures such as evacuation. We have concluded that:

> ***Conclusion 6: Flooding risks are unlikely to prevent construction of new nuclear power stations at potential development sites in the UK over the next few years. For sites with a flooding risk, detailed consideration may require changes to plant layout and the provision of particular protection against flooding.***

and that:

> ***Conclusion 7: There is no need to change the present siting strategies for new nuclear power stations in the UK.***

The new reactors being considered for the UK are designed to limit the chance and consequences of a major accident occurring in any one reactor unit. Thus we consider that there is no reason per se why multi-reactor plants, based on such designs should not be built. Nevertheless, we would require that the safety case for any multi-reactor site demonstrates that the risks of an accident in one reactor unit having adverse consequences for a neighbouring unit are acceptably remote, in line with the principle of *as low as reasonably practicable* (ALARP). Additionally, before a plant is allowed to operate, the pre-operational safety case will have to demonstrate that there is adequate capability (both human and equipment) to deal with postulated multi-event scenarios.

> ***Conclusion 8: There is no reason to depart from a multi-plant site concept given the design measures in new reactors being considered for deployment in the UK and adequate demonstration in design and operational safety cases.***

The cores of the Magnox and AGR reactors operating in the UK have larger thermal capacities and lower power densities than the Boiling Water Reactors at Fukushima. They therefore have longer timescales on loss of cooling before the operator or automatic systems have to react to stop the fuel overheating dangerously. In addition, hydrogen is not generated due to fuel cladding/water interactions if the fuel overheats during loss of cooling accidents (some small limited amounts of carbon monoxide, which is flammable, are produced in normal operation in gas-cooled reactors).

> ***Conclusion 9: The UK's gas-cooled reactors have lower power densities and larger thermal capacities than water cooled reactors which with natural cooling capabilities give longer timescales for remedial action. Additionally, they have a lesser need for venting on loss of cooling and do not produce concentrations of hydrogen from fuel cladding overheating.***

Reactor Unit 3 had some mixed oxide (MOX) fuel in the core, whereas the other affected reactors did not. There were reports of some very small quantities of plutonium being detected outside the Fukushima-1 site but upon analysis this was shown to be plutonium fallout from nuclear weapon testing some decades ago, and not from the Fukushima releases.

> ***Conclusion 10: There is no evidence to suggest that the presence of MOX fuel in Reactor Unit 3 significantly contributed to the health impact of the accident on or off the site.***

There is the potential to learn many lessons on human factors aspects from the Fukushima accident both from actions that assisted in developing an effective response and those that may have contributed to the development of the accident. Little information is available to date on how human actions contributed in one way or the other. However, it is clear that some exemplary and brave actions have been taken to try to bring the situation under control.

> ***Conclusion 11: With more information there is likely to be considerable scope for lessons to be learnt about human behaviour in severe accident conditions that will be useful in enhancing contingency arrangements and training in the UK for such events.***

Interim Report Recommendations

From our consideration of the events at the Fukushima-1 site we have identified various matters that we consider should be reviewed to determine whether there are any reasonably practicable improvements to the safety of the UK nuclear industry. Additionally, we have identified some more general matters for consideration. In formulating our interim report recommendations we have tried to group them into logical categories and to identify those who we expect to follow up the recommendations. The recommendations in full are listed below.

General	
International Arrangements for Response	**Recommendation 1:** The government should approach IAEA, in co-operation with others, to ensure that improved arrangements are in place for the dissemination of timely authoritative information relevant to a nuclear event anywhere in the world.
National Emergency Response Arrangements	**Recommendation 2:** The Government should consider carrying out a review of the Japanese response to the emergency to identify any lessons for UK public contingency planning for widespread emergencies, taking account of any social, cultural and organisational differences.
	Recommendation 3: The Nuclear Emergency Planning Liaison Group

	should instigate a review of the UK's national nuclear emergency arrangements in light of the experience of dealing with the prolonged Japanese event.
Openness and Transparency	**Recommendation 4:** Both the UK nuclear industry and ONR should consider ways of enhancing the drive to ensure more open, transparent and trusted communications, and relationships, with the public and other stakeholders.

Relevant to the Regulator	
Safety Assessment Approach	**Recommendation 5:** Once further detailed information is available and studies are completed, ONR should undertake a formal review of the Safety Assessment Principles to determine whether any additional guidance is necessary in the light of the Fukushima accident, particularly for "cliff-edge" effects.
Emergency Response Arrangements and Exercises	**Recommendation 6:** ONR should consider to what extent long-term severe accidents can and should be covered by the programme of emergency exercises overseen by the regulator.
	Recommendation 7: ONR should review the arrangements for regulatory response to potential severe accidents in the UK to see whether more should be done to prepare for such very remote events.

to the Nuclear Industry	
Off-site Infrastructure Resilience	**Recommendation 8:** The UK nuclear industry should review the dependency of nuclear safety on off-site infrastructure in extreme conditions, and consider whether enhancements are necessary to sites' self sufficiency given for the reliability of the grid under such extreme circumstances.
	Recommendation 9: Once further relevant information becomes available, the UK nuclear industry should review what lessons can be learnt from the comparison of the events at the Fukushima-1 (Fukushima Dai-ichi) and Fukushima-2 (Fukushima Dai-ni) sites.
Impact of Natural Hazards	**Recommendation 10:** The UK nuclear industry should initiate a review of flooding studies, including from tsunamis, in light of the Japanese experience, to confirm the design basis and margins for flooding at UK nuclear sites, and whether there is a need to improve further site-specific flood risk assessments as part of the periodic safety review programme, and for any new reactors. This should include

	sea-level protection.
Multi-reactor Sites	**Recommendation 11:** The UK nuclear industry should ensure that safety cases for new sites for multiple reactors adequately demonstrate the capability for dealing with multiple serious concurrent events induced by extreme off-site hazards.
Spent Fuel Strategies	**Recommendation 12:** The UK nuclear industry should ensure the adequacy of any new spent fuel strategies compared with the expectations in the Safety Assessment Principles of passive safety and good engineering practice.
Site and Plant Layout	**Recommendation 13:** The UK nuclear industry should review the plant and site layouts of existing plants and any proposed new designs to ensure that safety systems and their essential supplies and controls have adequate robustness against severe flooding and other extreme external events.
Fuel Pond Design	**Recommendation 14:** The UK nuclear industry should ensure that the design of new spent fuel ponds close to reactors minimises the need for bottom penetrations and lines that are prone to siphoning faults. Any that are necessary should be as robust to faults as are the ponds themselves.
Seismic Resilience	**Recommendation 15:** Once detailed information becomes available on the performance of concrete, other structures and equipment, the UK nuclear industry should consider any implications for improved understanding of the relevant design and analyses.
Extreme External Events	**Recommendation 16:** When considering the recommendations in this report the UK nuclear industry should consider them in the light of all extreme hazards, particularly for plant layout and design of safety-related plant.
Off-site Electricity Supplies	**Recommendation 17:** The UK nuclear industry should undertake further work with the National Grid to establish the robustness and potential unavailability of off-site electrical supplies under severe hazard conditions
On-site Electricity Supplies	**Recommendation 18:** The UK nuclear industry should review any need for the provision of additional, diverse means of providing robust sufficiently long-term independent electrical supplies on sites, reflecting the loss of availability of off-site electrical supplies under severe conditions
Cooling Supplies	**Recommendation 19:** The UK nuclear industry should review the need

	for, and if required, the ability to provide longer term coolant supplies to nuclear sites in the UK in the event of a severe off-site disruption, considering whether further on-site supplies or greater off-site capability is needed. This relates to both carbon dioxide and fresh water supplies, and for existing and proposed new plants.
	Recommendation 20: The UK nuclear industry should review the site contingency plans for pond water make up under severe accident conditions to see whether they can and should be enhanced given the experience at Fukushima.
Combustible Gases	**Recommendation 21:** The UK nuclear industry should review the ventilation and venting routes for nuclear facilities where significant concentrations of combustible gases may be flowing or accumulating to determine whether more should be done to protect them.
Emergency Control Centres, Instrumentation and Communications	**Recommendation 22:** The UK nuclear industry should review the provision on-site of emergency control, instrumentation and communications in light of the circumstances of the Fukushima accident including long timescales, wide spread on and off-site disruption, and the environment on-site associated with a severe accident.
	Recommendation 23: The UK nuclear industry, in conjunction with other organisations as necessary, should review the robustness of necessary off-site communications for severe accidents involving widespread disruption.
Human Capabilities and Capacities	**Recommendation 24:** The UK nuclear industry should review existing severe accident contingency arrangements and training, giving particular consideration to the physical, organisational, behavioural, emotional and cultural aspects for workers having to take actions on-site, especially over long periods. This should take account of the impact of using contractors for some aspects on-site such as maintenance and their possible response.
Safety Case	**Recommendation 25:** The UK nuclear industry should review, and if necessary extend, analysis of accident sequences for long-term severe accidents. This should identify appropriate repair and recovery strategies to the point at which a stable state is achieved, identifying any enhanced requirements for central stocks of equipment and logistical support.

Way Forward	
Way forward	**Recommendation 26:** A response to the various recommendations in the interim report should be made available within one month of it being published. These should include appropriate plans for addressing the recommendations. Any responses provided will be compiled on the ONR website.

Way Forward

In response to a request from the Council of the European Union, work is underway to develop “stress tests” for nuclear power stations. This will involve national regulators requiring operators to undertake such examinations of safety margins. The national regulators will independently assess the results. In the UK we would then require improvements in line with the “as low as reasonably practicable” (ALARP) principle.

There may well be overlaps between these “stress tests” and the recommendations in this report. Hence it is recommended that the nuclear industry produce a common plan for responding to the ”stress tests” as well as the recommendations in this report. We would expect this plan will be published.

The outcome of this work and that of the “stress tests” should be published along with proposals for any reasonably practicable improvements to plant, people or procedures that may emerge. Given the timescales for the “stress tests” there will be need for a supplement to our final report to take account of their outcome.

The final report will look at any specific implications of the Fukushima accident for all nuclear installations in the UK. It will also report on the submissions we have received.