Office for Nuclear Regulation

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Japanese earthquake and tsunami: Implications for the UK Nuclear Industry

Interim Report

HM Chief Inspector of Nuclear Installations

18 May 2011

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In preparing this report I am indebted to many colleagues in the Office for Nuclear Regulation (ONR), those outside of ONR who have taken the time to provide submissions of many types, and members of the Technical Advisory Panel that I set up to provide independent authoritative advice.

I am also very grateful to many dedicated scientists and engineers of other agencies and government bodies whose excellent work I have had access to.

Mike Weightman
HM Chief Inspector of Nuclear Installations
May 2011

Foreword

On 11 March 2011 Japan suffered its worst recorded earthquake, known as the Tohuku event. The epicentre was 110 miles East North East from the site of the Fukushima-1 site. Reactor Units 1, 2 and 3 on this site were operating at power before the event and on detection of the earthquake shutdown safely. Initially on-site power was used to provide essential post-trip cooling. About an hour after shutdown a massive tsunami from the earthquake swamped the site and took out the AC electrical power capability. Sometime later alternative back-up cooling was lost. With the loss of cooling systems, Reactor Units 1 to 3 overheated as did a spent fuel pond in building of Reactor Unit 4. This resulted in several disruptive explosions because overheated zirconium cladding reacted with water and steam generated hydrogen. Major releases of radioactivity occurred, initially by air but later by leakage to sea. The operators struggled to restore full control.

This was a serious nuclear accident, with a provisional International Nuclear Event Scale (INES) level 5, and has since been amended to a provisional level 7 (the highest level). The Japanese authorities instigated a 20km evacuation zone, a 30km sheltering zone and 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 to protect the citizens of the UK. Many agencies, government departments and individuals were involved in providing their best technical advice to the UK Government. 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 - on 1 April 2011), provided authoritative advice on nuclear aspects throughout the crisis.

This interim report responds to the request[a] of the Secretary of State for Energy and Climate Change to examine the circumstances of the Fukushima accident to see what lessons could be learnt to enhance the safety of the UK nuclear industry. I was asked to provide an interim report to be available by the middle of May 2011 and a final report within six months. The Secretary of State requested co-operation and co-ordination with international colleagues in the research and compilation of the report.

At the time of writing the Japanese people are still dealing with the terrible aftermath of the earthquake and tsunami. Workers at the Fukushima-1 site are still endeavouring to bring the situation fully under sustained control. The Japanese government is additionally extending its efforts to deal with the longer term impact of the accident on the environment, the people, and the economy. Consequently, not everything is known about the circumstances and contributory factors. However, the broad facts are available, analysis has been undertaken, and major lessons can be learnt. It is in this context that this interim report focuses on significant lessons for the safety of nuclear power stations operating in the UK and proposals to build new ones. It does not examine nuclear policy issues that are matters for politicians and outside my organisation's competence and role. It looks at the evidence and facts, as far as they are known at this time, to establish technically based issues that relate to possible improvements in safety and regulation in the UK. It also indicates some lessons for international arrangements for such systems.

The final report will be wider, covering any lessons to be learnt for the safety of all types of nuclear installations in the UK. Both reports will link into other work underway or planned which seeks to learn lessons such as the European Council "stress tests" and the work of the Nuclear Energy Agency (NEA) of the

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[a] Letter from the Secretary of State for Energy and Climate Change to HM Chief Inspector 14 March 2011.

Organisation for Economic Co-operation and Development (OECD) and the International Atomic Energy Agency (IAEA).

Mike Weightman
HM Chief Inspector of Nuclear Installations
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.

Relevant to the Regulator	
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.

Relevant 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.

Relevant to the Nuclear Industry	
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.

Contents

INTRODUCTION

1 This report ("HM Chief Inspector's Interim Fukushima Report") looks at the immediate lessons for the UK nuclear industry that can be learnt from the accident that took place at the Fukushima-1 site in Japan. We have worked, and expect to continue to work, in co-operation and co-ordination with national stakeholders and international colleagues. Annex A contains details of the main areas of international co-operation.

2 As noted earlier there will be two stages in the production of the report; this interim report and a final report by mid September 2011.

3 This report provides a brief background to radioactive hazards, and how to protect against them, as well as an overview of nuclear power technology and the approach to nuclear safety and security in the UK, internationally and in Japan. We also describe how we have taken forward the work so far and how we expect to continue to the final report. The report also describes who we have liaised with to date and describes the measures we have put in place to provide for external scrutiny of our work.

4 Even at this early stage there are some emerging lessons and these are recorded together with recommendations for further work.

5 It is important to note that even at the time of the final report not everything may be known. Any developments will be closely monitored after the publication of the final report to maximise learning. The intention is to produce a supplement to the final report, to cover such matters as closeout of recommendations and the outcome of "stress tests" initiated by the European Council.

Aims of the Report

6 The HM Chief Inspector intends that both the interim and final reports will:

- Be independent and impartial without fear or favour for any particular stakeholder or group of stakeholders in line with his duty.
- Be open and transparent and be published with public access to all contributions as far as security and other considerations (such as the willingness of those submitting evidence or information to allow open disclosure).
- Be based on engagement with stakeholders to ensure that all relevant information and issues are covered.
- Be evidence and fact based, utilising the best scientific and technical advice available including that of expert groups.
- Be subject to robust technical governance via a Technical Advisory Panel (TAP).
- Examine the circumstances of, and factors contributing to, the accident at the Fukushima-1 site as far as they are known, and the responses to them.
- Draw on our close working with other nuclear regulators and international organisations.
- Provide an understanding of the circumstances of the event and the various responses to it to identify any lessons for enhancing the safety of UK nuclear facilities and infrastructure.

Scope

7 It is not possible at this stage to define the final scope of the report. The events in Japan are still unfolding and issues may still emerge over the coming days or weeks. Because of this we have not been able to verify all facts, statements or submissions for this interim report.

8 The scope for this interim report is necessarily limited compared to that of the final report given the timing and state of knowledge. In it we only cover the immediate lessons to be learnt for existing nuclear power plants in the UK and for any new nuclear power plants that may or may not be built based on the information about the event available up to the middle of April 2011.

9 The reports will not address nuclear or energy policy issues as these are rightly within the province of the Government and Parliament and are outside the role and responsibilities of the nuclear regulator.

10 The report does not constitute a public inquiry into the nuclear industry or nuclear new build but is a technically led and scientifically informed assessment of the lessons to be learnt from the Fukushima accident with a view to securing and enhancing the continuous improvement in the safety of the UK nuclear industry, associated infrastructure, and regulation.

Relevant Additional UK Responses

11 In response to the Fukushima accident, the UK established The Cabinet Office Briefing Room (COBR) which met for the first time on 11 March 2011, with the Foreign and Commonwealth Office (FCO) in the lead and representation from other departments and agencies including the Department of Energy and Climate Change (DECC), Department of Health (DoH), and HSE/ONR. COBR continued to meet until early April 2011.

12 The Government Chief Scientific Adviser, Sir John Beddington, chaired a Scientific Advisory Group for Emergencies (SAGE), which started meeting on 13 March 2011 to address requirements for advice to UK nationals in Japan.

13 The HSE Incident Suite in Bootle was staffed from the first day of the accident for over two weeks, at times operating on a 24 hour basis. It acted as a source of expert regulatory analysis, advice and briefing to central Government departments and SAGE. To ensure the FCO was able to readily call on technical expertise in developing advice to nationals in Japan, an ONR nuclear specialist was embedded within the FCO Crisis Team for the first week of the accident.

14 DECC activated relevant elements of the UK's Overseas Nuclear Accident Response Plan, setting up an emergency briefing team on 15 March 2011 to manage the demand for information. As part of this response, DECC called and chaired a technical coordination centre, inviting key organisations in the multi-agency response - i.e. the Department for Environment, Food and Rural Affairs (Defra), the Health Protection Agency, the Meteorological Office, the national radiation monitoring network (known as RIMNET), the Food Standards Agency, the Environment Agency, Government Office for Science - to regular telephone conferences to ensure that media messages were properly coordinated. The emergency briefing team was stood down at the beginning of April 2011 with DECC managing the response under normal business arrangements.

15 In response to the Secretary of State's (SoS) request to the Chief Inspector, ONR has set up a dedicated project team, including a technical support team, covering aspects of the Fukushima accident 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.

16 Immediately following the notification of the accident in Japan, ONR quickly sought assurance from the UK nuclear industry by asking all nuclear site licensees to promptly answer the following four questions:

- How confident are you of the robustness of your plant cooling systems and their capabilities for maintaining plant safety in normal, upset and emergency conditions?
- How confident are you that your plant could safely withstand infrequent seismic events in the UK, do you have systems for detecting such events and initiating protective actions and if so what actions do you take to ensure that these systems are fully available?
- Are you confident that plant safety systems and safety-related systems are capable of maintaining critical safety functions (criticality, cooling and containment) in the event of foreseeable external hazards, in particular flooding?
- If hydrogen or other combustible gases could be generated by the plant under normal, upset or emergency conditions, do you have robust systems for detecting them and initiating protective actions and what actions do you take to ensure that these systems are fully available?

17 In addition ONR has actively sought assistance from a wide range of stakeholders by issuing a broad invitation to anyone able and willing to assist via written submissions.

18 The responses we received up to 15 April 2011 are being published on our website and the contributions considered as part of our work.

19 In order to provide independent nuclear 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). Details about the TAP, including its membership and terms of reference can be found via www.hse.gov.uk/nuclear.

BACKGROUND

20 In considering lessons to be learnt from this particular nuclear accident, the following provides some explanation of the concepts and approach involved in securing the protection of people and society from radiation hazards both naturally occurring and those generated or enhanced by human activities.

General Background

Hazards, Hazard Potential, Barriers and Risks

21 Hazard and risk are often used interchangeably in everyday vocabulary. In common with other UK regulatory bodies, ONR finds it useful to distinguish between hazard and risk by considering a hazard as something (e.g. an object, a property of a substance, a phenomenon or an activity) that can cause harm and risk as the chance that an individual or something that is valued will be adversely affected by the hazard. We are all exposed to various hazards in our everyday life and we know there is no such thing as zero risk. We also know that however remote a risk may be it could turn up.

22 Just because a hazard exists does not mean that we will be exposed to it or that it will be realised. For example, a hazardous substance may have intrinsic toxicity but the form of that substance may make it more benign. Even if it is in solid form, for it to cause harm to a human being, it has to be inhaled, and even though it may contain the same amount of toxic substance as if it were in a gaseous form, it is less intrinsically harmful. This is sometimes covered by talking about hazard potential that takes account of the form of the hazardous substance, gaseous or aerosol, liquid or solid.

23 The form of a substance is just one example of a barrier that may protect us from harm from hazards. Others can be temporal (the time people are exposed to that hazard, such as crossing a road); spatial (people are not in the vicinity of or in the range to which the hazard extends, such as the distance from a fire, explosion or source of gamma radiation); engineered (fences to keep people away from rail tracks or roads); or administrative (instructions, rules, laws that are there to prevent people from being harmed).

24 The existence of a barrier does not mean that we will not suffer harm from the hazard, as the barrier might fail (the exception being those that cannot fail because they are founded on the fundamental laws of nature).

25 To take account of all these aspects of protecting people from the harm of hazards and so be deemed to be safe we use the term risk, which can be considered to be the combination of the chance of a hazard being realised and the chance of human beings being exposed to it. It is normally expressed in terms of chance of death of an individual per year. Risks to groups of individuals or populations or the fabric of society are societal risks rather than individual risks. Society normally has more concern proportionately about societal rather than individual risks. Risks to the environment are also of great concern.

26 Above, we noted that we are all exposed to hazards of one type or another. Some examples of the historical risks associated with various hazards are provided in Annex B, and further discussion on risk and hazard is provided in HSE publication *Reducing Risks, Protecting People* (Ref. 1).

Radiation, Radioactivity and Risk to Humans from Exposure

27 Nuclear power stations use the energy from splitting atoms of uranium or plutonium (fission) to generate electricity. Fission also results in fission products, which are particular types of other elements or nuclides, and ionising radiation. Fission products themselves can also decay to other elements giving rise to ionising radiation and energy. The rate of radioactive decay and energy release determines how potentially harmful a radioactive substance is. Another important property of a radioactive substance is its half life – the time it takes for a radioactive substance to reduce its radioactivity by half. This can range from seconds to millions of years depending on the particular nuclide.

28 Radioactive substances can interact with humans through different routes (direct exposure, ingestion, inhalation, through wounds) and in different ways through different organs where it may be accumulated. Additionally, radioactive substances ingested or inhaled into the body can with time be excreted and hence exposure can reduce or stop altogether. The degree of harm to a human being is dependent upon the combination of these factors and is highly complex but there are internationally recognised models (via the International Commission for Radiation Protection (ICRP)) for exposure and harm from ionising radiation.

29 Potential harm to an individual is normally considered to be one of two types – either acute harm (non-stochastic effects such as vomiting, and at high enough exposures death) and latent harm in the form of increased risk of cancer of various types (stochastic effects) some of which lead to death, or possible genetic effects to progeny.

30 Non-stochastic effects are usually only seen in individuals in close proximity to either a nuclear accident (such as workers near a criticality accident) or as a result of exposure to a highly radioactive source. Nuclear emergency planning is based on the prevention of non-stochastic effects and limiting the risk associated with stochastic effects.

31 Stochastic effects, which are the same whether radiation is natural or man-made, are based on a linear dose risk model; in which it is assumed that the increase in risk of eventually developing cancer is directly proportionate to the increase in exposure to ionising radiation, no matter how small that increase may be. The units of exposure are sieverts. A dose of one sievert equates to an increased chance of getting cancer of about 1 in 20. The normal chance of dying from cancer naturally or from other causes is about 1 in 4.

32 A sievert is a very large exposure. Radiation workers in the UK are exposed on average to around one thousandth of a sievert annually (or one milli-sievert). This is additional to the approximately 2.5 milli-sieverts per year we all incur, on average, from normal background and other means. This natural exposure to radiation varies around the country with some areas, such as Cornwall, giving rise to annual natural background exposures around four times the average (i.e. 10 milli-sieverts). We also incur increased radiation doses when we fly, when we eat certain natural foods, when we have medical diagnostic x-rays, etc. The regulatory limits for normal radiation exposure from nuclear power stations are 20 milli-sieverts for radiation workers on the plants and one milli-sievert for members of the public who may be exposed by discharges and direct radiation from the plant. In practice, the application of the legal requirement in the UK to reduce risks so far as is reasonably practicable, means that exposure are substantially below such limits. Annex C provides some information on typical exposures to ionising radiation from different activities.

Protection against Radiation

33 To protect against exposure to radiation from a nuclear reactor there are three main aspects in which to consider barriers to:

- Contain the radiation or radioactive material (by shielding such as massive concrete shield wall to stop or absorb the radiation, and/or containment structures such as robust vessels, cells, flasks to stop radioactive material getting into the workplace or environment).
- Cool the radioactive material to make sure it doesn't degrade the containment to such an extent that the radioactive material escapes.
- Control nuclear reactions and chemical reactions associated with the nuclear material to ensure the energy released in these does not degrade the containment and hence release radioactive material or increase radiation levels.

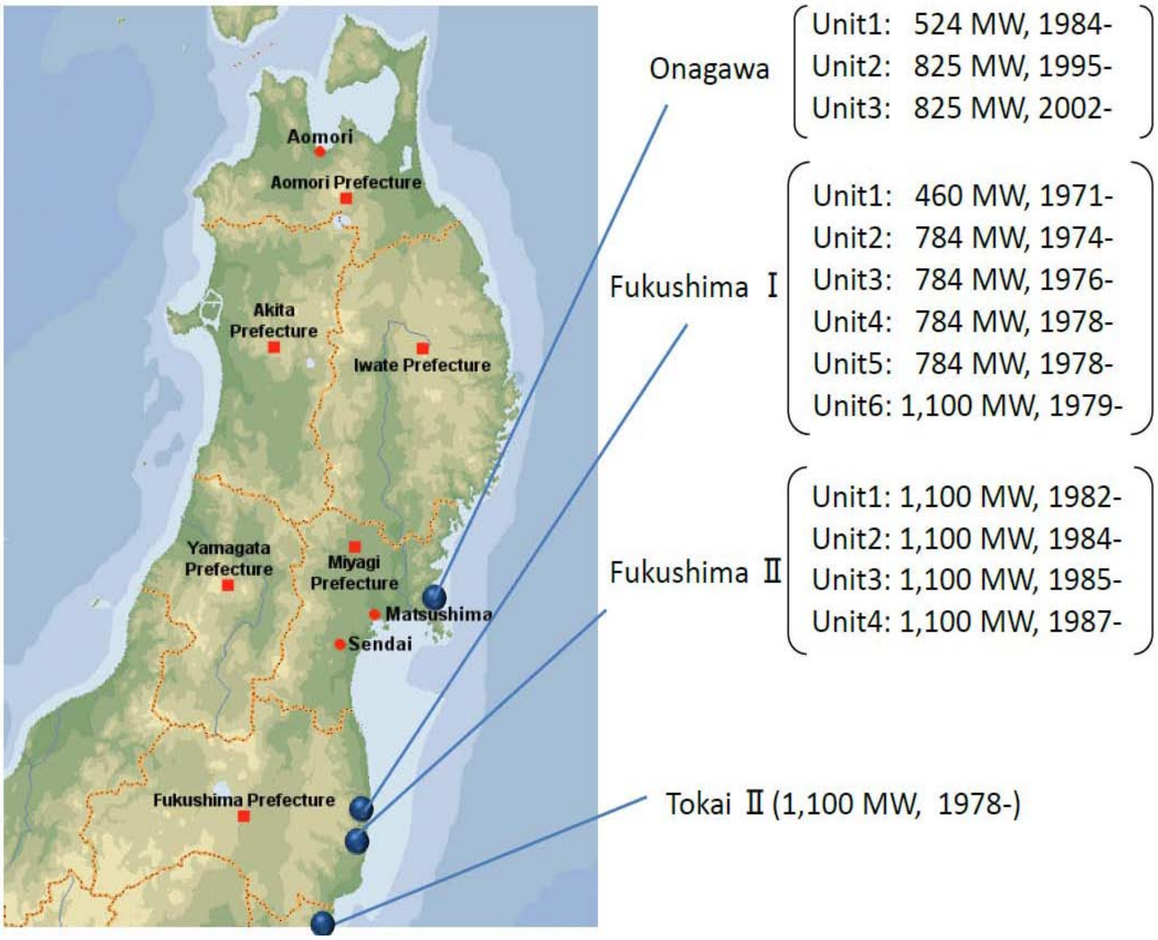
Nuclear Power Stations

34 In nuclear power stations the heat from nuclear fission is used to produce steam to drive turbines which in turn generate electricity. Different types of reactor generate the steam through different means. In a Boiling Water Reactor (BWR) the steam is generated directly from the water used to cool the fuel elements (uranium oxide or uranium oxide mixed with plutonium oxide encased or clad in zirconium alloy) in the reactor. In a Pressurised Water Reactor (PWR) the fuel is cooled by water in the primary circuit which then generates steam in a secondary circuit via steam generators and it is the steam from this secondary system that drives the turbines.

35 In the UK a third type of reactor has been deployed – gas-cooled reactors which use carbon dioxide gas to take the heat away from the fuel. The carbon dioxide then heats water in boilers to generate steam for the turbines. Within a reactor environment carbon dioxide is not susceptible to phase change (e.g. water to steam - which under some fault conditions can adversely affect the heat transfer capabilities of BWRs and PWRs). The gas-cooled reactors operating in the UK are four Magnox reactors (two at Wylfa and two at Oldbury) and 14 Advanced Gas-cooled Reactors (AGR) across the country. The UK's only water cooled nuclear power reactor is at Sizewell B, which is one of the most modern PWRs operating worldwide.

36 Across the world there are more than 400 nuclear power reactors operating with over 140 operating in Europe and 54 in Japan. **Figure 1** shows the nuclear power reactors in the area affected by the 2011 earthquake and tsunami.

Figure 1: Nuclear Power Reactors in the Area Affected by the 2011 Earthquake and Tsunami



Safety of Nuclear Power Reactors

37 For nuclear power reactors the hazard potential derives from the large inventory of radioactivity in the fuel together with the heat energy from nuclear fission.

38 To protect against this hazard potential, nuclear power reactor designs employ barriers to preserve all three radiation safety functions – containment, cooling and control.

39 The strategy used for nuclear safety is to use a defence in depth approach in which the design will aim to: prevent faults occurring, provide protection to control the faults should they still occur, and then provide means to mitigate the consequences should the protection fail. This approach is illustrated in the table below extracted from ONR's Safety Assessment Principles (SAP) (Ref. 2), which are the technical principles which ONR uses to judge licensees' safety cases.

Table 1: Levels of Defence in Depth and means of achieving them

Level	Objective	Essential means
Level 1	Prevention of abnormal operation and failures by design	Conservative design, construction, maintenance and operation in accordance with appropriate safety margins, engineering practices and quality levels
Level 2	Prevention and control of abnormal operation and detection of failures	Control, indication, alarm systems or other systems and operating procedures to prevent or minimise damage from failures
Level 3	Control of faults within the design basis	Engineered safety features, multiple barriers and accident or fault control procedures
Level 4	Control of severe plant conditions in which the design basis may be exceeded, including the prevention of fault progression and mitigation of the consequences of severe accidents	Additional measures and procedures to prevent or mitigate fault progression and for accident management
Level 5	Mitigation of radiological consequences of significant releases of radioactive substances	Emergency control and on- and off-site emergency response

Design Basis Analysis

40 Conservative design, good operational practice and adequate maintenance and testing should minimise the likelihood of faults. Nevertheless they could still occur so the design of nuclear facilities must be shown to be capable of tolerating them. The design should be able to tolerate or withstand a wide range of faults. This is known as the *design basis*. During the design and review process, initiating events are systematically identified and analysed to determine the nature and strength of the barriers required. Initiating events can be internal faults within the power station, or external events such as extreme weather conditions or earthquakes. The process whereby the designer aims to ensure that the reactor can withstand fault sequences arising from the identified initiating events is called Design Basis Analysis (DBA). The DBA is a robust, deterministic demonstration of the fault tolerance of the facility and the effectiveness of its safety measures. In the UK criteria for design basis analysis are set out in our SAPs (Ref. 2).

Probabilistic Safety Analysis and Severe Accidents

41 The overall risk is addressed by Probabilistic Safety Analysis (PSA). PSA provides an integrated, structured framework for safety analysis which allows comparisons to be made against ONR's numerical targets and supports the DBA by providing a systematic means for examining dependencies and complex interactions between systems as well as providing insights on the balance of the design.

42 ONR's SAPs define severe accidents as those fault sequences that lead to consequences beyond the highest radiological consequences in the DBA Basic Safety Levels or a substantial unintended relocation of radioactive material that places a demand on the integrity of the remaining barriers. Robust application of DBA should ensure that severe accidents are highly unlikely. Nevertheless, the principle of defence in depth requires that fault sequences leading to severe accidents are analysed and provision made to address their consequences. In common with the PSA, analysis of severe accidents is performed on a best estimate rather than conservative basis as this analysis is used to derive realistic guidance on the actions to be taken in the event of such an accident occurring. The PSA and Severe Accident Analysis may identify that further plant or equipment is required in addition to that analysed within the DBA.

43 The Fukushima accident was a severe accident and this report is concerned with the potential lessons to be learnt from it for the UK. This does not necessarily mean that DBA and severe accident approaches currently used in ensuring nuclear safety are inherently wrong. However, there may be lessons on the nature and scope of the design basis itself that need to be taken into account and further protection provided. Further information and analysis will be required to consider such matters.

UK Regulatory Approach and Standards

44 The regulation of the safety of nuclear installations in the UK is through a system of control based on a licensing regime by which a corporate body is granted a licence to use a site for specified activities. This allows for the regulation by ONR of the design, construction, operation and decommissioning of any nuclear installation for which a nuclear site licence is required under the Nuclear Installations Act 1965 (NIA65). Such installations include nuclear power stations, research reactors, nuclear fuel manufacturing and isotope production facilities, fuel reprocessing and the storage of radioactive matter in bulk. Nuclear site licences are granted for an indefinite term and one licence may cover the lifetime of an installation, which includes certain defence nuclear installations, from siting through to eventual completion of decommissioning.

45 NIA65 allows ONR to attach to each nuclear site licence such conditions as it considers necessary or desirable in the interests of safety or with respect to the handling, treatment or disposal of nuclear materials. ONR has developed a standard set of 36 conditions which are attached to all nuclear site licences. In the main they require the licensee to make and implement adequate arrangements to address the particular issues identified. The licence conditions (LC) provide the legal basis for regulation by ONR. They do not relieve the licensee of the responsibility for safety. The LCs are largely non-prescriptive and set goals that the licensee is responsible for achieving.

46 One of the main functions of ONR is to carry out inspections at licensed sites, and at the licensee's corporate headquarters and elsewhere. These enable ONR to check compliance with LCs and other legal requirements, and provides a basis for enforcement and other regulatory decisions. Inspectors also seek to advise and encourage the operators of plants to enhance safety where this is consistent with the "as low as reasonably practicable" (ALARP) principle.

47 One of the requirements of the LCs is that the licensees produce an adequate safety case to demonstrate that facilities are safe in both normal operation and fault conditions. The safety case is a fundamental part of the licensing regime at all stages in the lifecycle of a nuclear installation. It establishes whether a licensee has demonstrated that it understands the hazards associated with its activities and how to control them adequately. The technical principles, which ONR uses to judge licensees' safety cases, are contained in the SAPs (Ref. 2). The latest version of the SAPs,

originally published in 2006, were benchmarked against extant International Atomic Energy Agency (IAEA) safety standards.

48 In the areas relevant to the accident at the Fukushima-1 site, the SAPs set out clear regulatory expectations for the safety case and design basis events in relation to hazards such as extreme weather, flooding, earthquakes, fire, explosion etc, and the provision of essential services.

49 In the UK the operator of a nuclear installation is also required by the LCs to periodically review its safety case for the plant. This Periodic Safety Review (PSR) usually takes place at 10 yearly intervals and requires the operator to demonstrate that the original design safety intent is still being met. It is then required to be assessed against the latest safety standards and technical knowledge. The operating experience of the plant is also considered, to see whether there are any reasonably practicable safety improvements that should be made or if there are any life limiting factors that would preclude operation for a further 10 years. The PSR includes a review of the safety of the plant in response to events such as earthquakes, floods, fire and explosion. ONR independently assesses licensees' PSR reports against its SAPs.

Japanese Nuclear Industry

50 In Japan, as of the end of March 2010, a total of 54 nuclear power reactors (30 BWRs and 24 PWRs) were operating. In addition, two reactors were being constructed.

51 BWRs and PWRs have been equally operated in a balanced manner, and four ABWRs (advanced BWRs) have been commissioned and the construction of APWRs (advanced PWRs) has been planned. Additionally, the commissioning of the fast breeder prototype reactor, which has been developed as the next-generation reactor, was resumed in May 2010. Furthermore, the decommissioning of nuclear installations that have ceased operation has been progressing.

Japanese Regulatory Regime

Legal Framework

52 Japan has an established legal framework, which is largely based on international standards and requirements such as the obligations set out in the Convention on Nuclear Safety (Ref. 3). However, there are some differences as reported in the IAEA International Regulatory Review Service (IRRS) report on the Japanese system (Ref. 4).

Japanese Regulatory Bodies

53 The nuclear safety regulatory bodies in Japan comprises two main organisations; the Nuclear Safety Commission (NSC), which is made up of five commissioners appointed by the Prime Minister, and the Nuclear and Industrial Safety Agency (NISA). The NSC provides high-level supervision of NISA. While the NSC operates within the Cabinet Office, NISA reports directly to the Ministry of Economy, Trade and Industry (METI). The Ministry of Education, Culture, Sports, Science and Technology (MEXT) also has a role in nuclear energy research and development and advice on nuclear safety matters.

54 The Minister of METI is responsible for the safety regulation of Japanese nuclear installations and has the authority to issue licenses to install nuclear installations. The Minister also has the authority to specify the details of the safety regulations, including measures for the safe operation

and physical security of nuclear fuel materials and the Operational Safety Program (OSP), including measures to be taken in an emergency. The Minister also has the authority to revoke a nuclear licence, order measures to improve operational safety, implement orders relating to emergency preparedness.

55 The Minister of METI delegates regulatory responsibility to NISA, which independently makes decisions or consults with the Minister of METI on proposed decisions. Before NISA issues a licence for a reactor installation, it consults both the Atomic Energy Commission (AEC), which is responsible for developing policies and strategies relating to nuclear power and advising on the application of permission criteria, and the NSC. This is intended to ensure independent supervision of NISA's implementation of safety regulation.

Nuclear and Industrial Safety Agency

56 NISA is an agency of METI established to ensure the safety of nuclear installations.

57 In carrying out its statutory functions, NISA performs periodic inspections to ensure facilities meet the appropriate standards and conform to the Operational Safety Program (OSP). The OSP is approved by NISA and "*prescribes procedures of operational management, operational limits and safety education of personnel, designates Chief Reactor Engineers, Chief Electrical Engineers and Chief Engineers of Boiler and Turbine, who supervise the safety of the operation, and the Persons Responsible for Operation, and notify NISA of them*". NISA also has a role in regulating nuclear emergency preparedness and response.

58 NISA has approximately 370 staff engaged in nuclear safety regulation, of which 110 are Nuclear Safety Inspectors and Senior Specialists for Nuclear Emergency Preparedness stationed at nuclear sites. By way of contrast ONR has 450 staff of which 220 are nuclear safety inspectors but comparisons should not be made giving differing scope of duties**.**

Technology Used at the Fukushima-1 Site

59 This section provides a high-level overview of the technologies employed at the Fukushima-1 site. More detailed descriptions of the key systems involved in the accident's chain of events are provided later in the report.

60 In general, the information regarding BWR technology provided in this report has been extracted from Refs 18, 19 and 20. The factual accuracy of this section is being checked by GE Hitachi Nuclear Energy and we will correct any inaccuracies or errors in the final report.

61 Although all the Fukushima-1 reactor units are BWRs designed by General Electric, there are design differences between them. Key characteristics of the six units (Ref. 22), which will be referred to later in the following paragraphs, are given in the table below.

Table 2: Summary of Fukushima-1 BWR Types and Electrical Output

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6
Reactor model	BWR-3 (*)	BWR-4	BWR-4	BWR-4	BWR-4	BWR-5
Containment model	Mark I	Mark I	Mark I	Mark I	Mark I	Mark II
Electrical Output (MWe)	460	784	784	784	784	1100
Commercial Operation	1971	1974	1976	1978	1978	1979

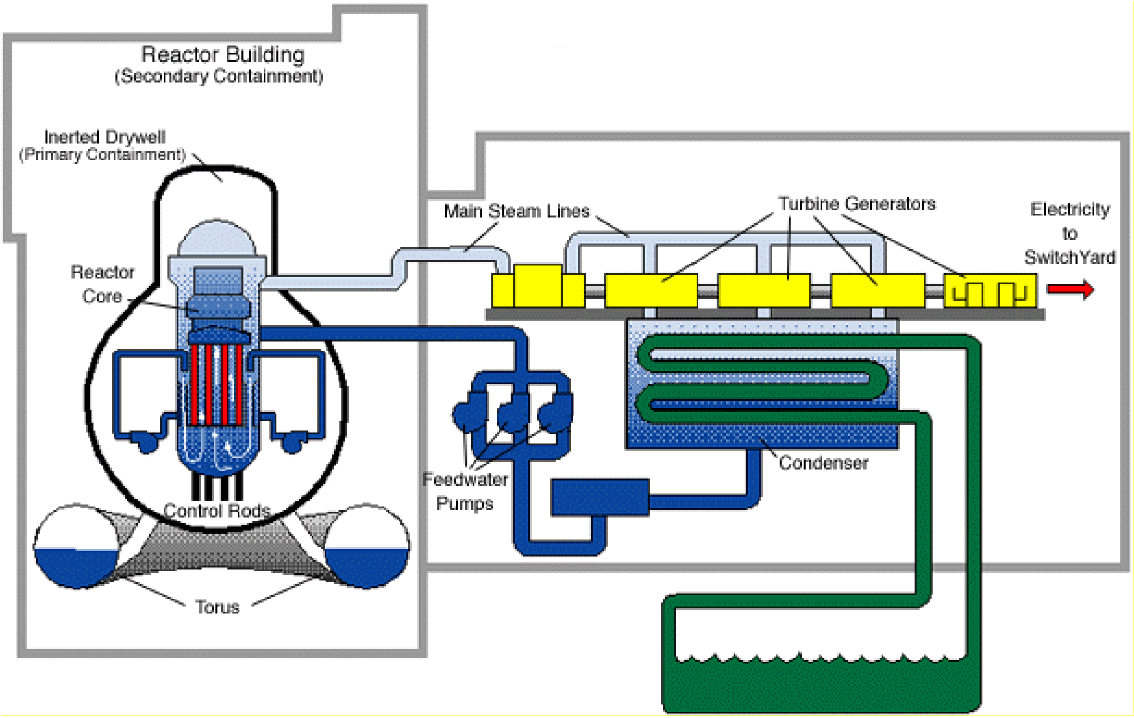
(*) Fukushima-1 Unit 1 is an early BWR-3 model that has a number of features of the earlier BWR-2 model.

62 BWRs are Light Water Reactors (LWR) in which normal water serves both as the reactor coolant and the moderator. The other big group of LWRs are PWRs.

Normal Operational Cooling

63 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, which 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 seawater passing through the secondary side. Once condensed, the water is pumped back into the reactor vessel starting the cycle all over again (**Figure 2**).

Figure 2: Cooling Schematic of a Boiling Water Reactor *(figure courtesy of GE Hitachi Nuclear Energy)*



64 The BWR reactor vessel (**Figure 3**) is a cylindrical shell with an integral rounded bottom head and a removable top head. It contains the reactor core and a number of internal structures. BWRs typically operate at a water/steam temperature of approximately 300°C and a pressure of around 75 times atmospheric pressure.

Figure 3: Boiling Water Reactor Vessel *(figure courtesy of GE Hitachi Nuclear Energy)*

65 The reactor core is made up of fuel assemblies, control rods and neutron monitoring instruments. To control the flow of coolant through the core, and to change the reactor power level relatively quickly, all the BWR models 2 to 6 vary the flow of coolant water through the core. All Fukushima-1 reactor units have two external recirculation loops with variable speed recirculation pumps and jet pumps internal to the reactor vessel. Coolant flow is controlled by changing the speed of the

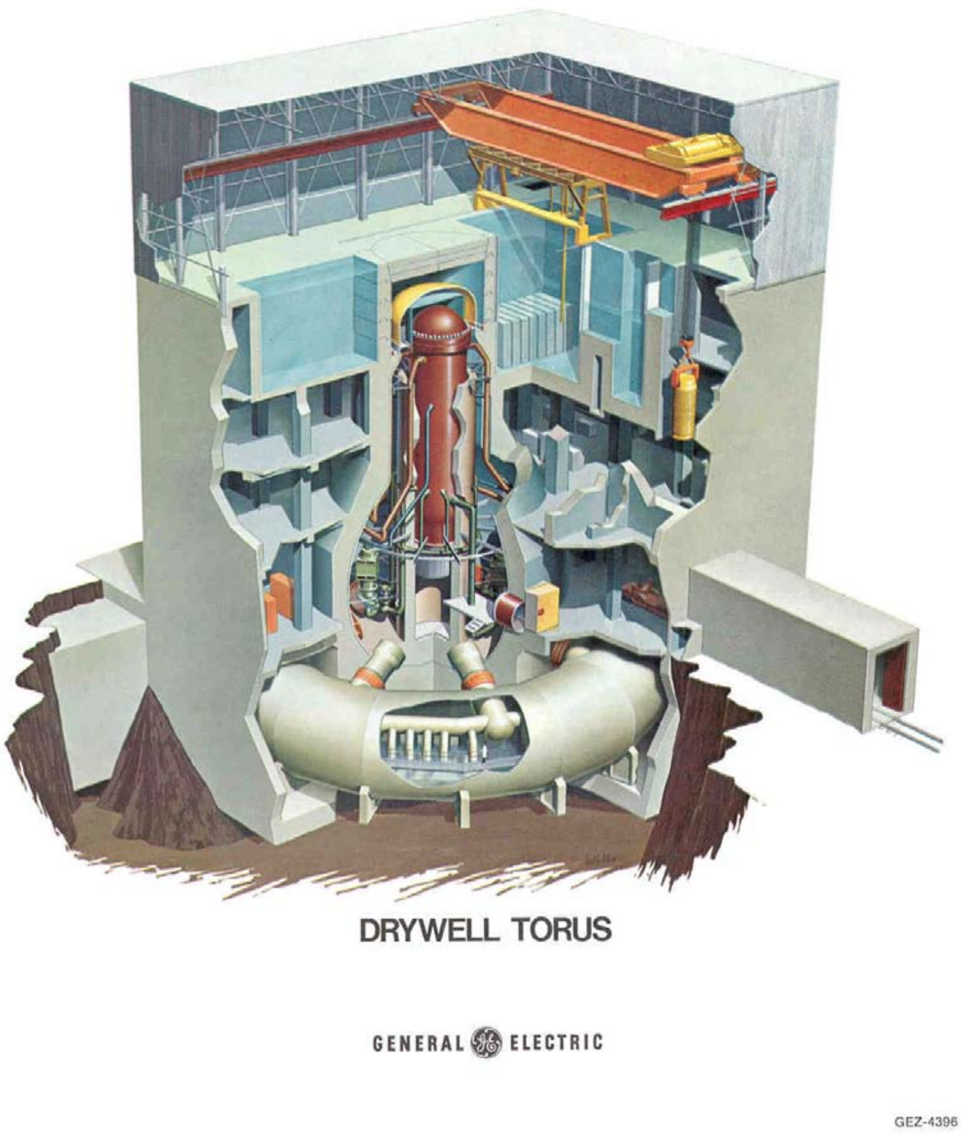
external recirculation pumps. Reactor power can also be controlled by movement of the control rods, which enter the core through the bottom of the reactor pressure vessel.

Containment

66 The reactor pressure vessel and its associated recirculation loops for each of the reactor units are housed in a Containment Vessel or Drywell, which is a structure designed to withstand high pressures.

67 Fukushima-1 Reactor Units 1 to 5 have a Mark I Containment with a drywell that resembles the shape of a light bulb (**Figure 4**). The Mark I Drywells are built of steel and surrounded by a concrete structure.

Figure 4: Schematic Cut-away of Mark I BWR *(figure courtesy of GE Hitachi Nuclear Energy)*

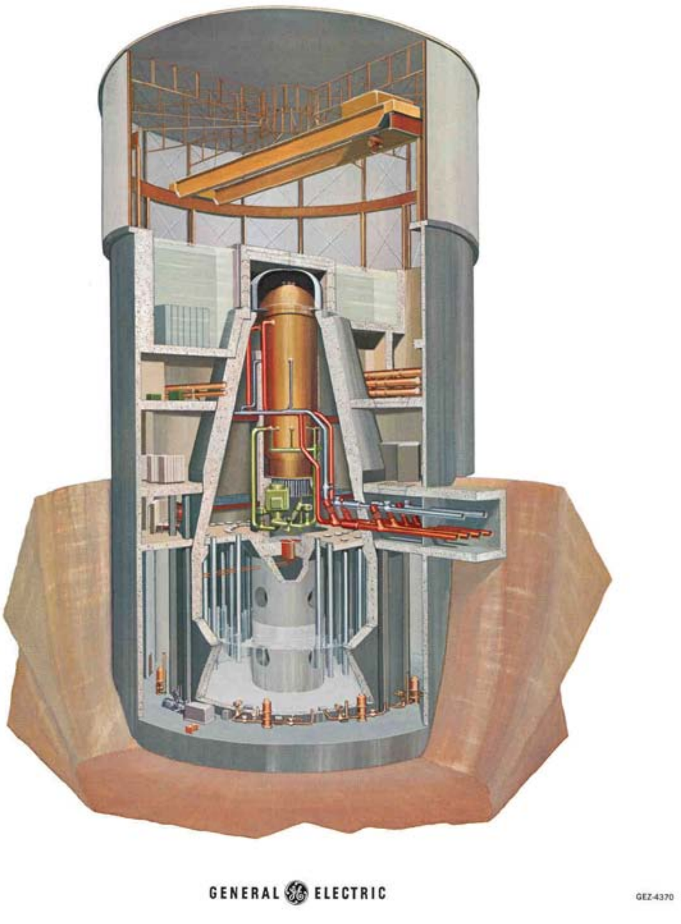


68 Fukushima-1 Reactor Unit 6 has a Mark II containment which consists of a steel dome head and concrete wall (post-tensioned or reinforced) standing on a basemat of reinforced concrete. The inner surface of the containment is lined with a steel plate that acts as a leak-tight membrane. The drywell has the form of a truncated cone.

69 Both Mark I and II containment models have suppression chambers with large volumes of water. The function of these water pools is to remove heat if an event occurs in which large quantities of steam are released from the reactor vessel. 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 steel structure that has the shape of a large doughnut and is located at the bottom of the drywell surrounding it. There is an interconnecting vent network between the drywell and the suppression chamber (**Figure 4**). The function of these vents is to channel steam from the drywell to the suppression pool (in case of a loss of coolant accident) but also to allow non-condensable gases such as hydrogen to be vented back to the drywell. The drywell and the torus are designed to withstand the same pressure.

70 The Mark II design (Reactor Unit 6) is an over-under configuration in which the suppression pool, of a cylindrical shape, is located directly below the drywell. The suppression chamber is cylindrical and separated from the drywell by a reinforced concrete slab. The drywell atmosphere is vented into the suppression chamber through a series of down-comer pipes penetrating and supported by the drywell (**Figure 5**). As for the Mark I containment, the drywell and the suppression pool are designed to withstand the same pressure.

Figure 5: Schematic Cut-away of Mark II BWR *(figure courtesy of GE Hitachi Nuclear Energy)*



71 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 (**Figure 4** and **Figure 5**). The secondary containment in both the Mark I and Mark II models form part of the reactor building. The building above the top of the reactor/drywell is lightweight in nature and not designed to provide a barrier function (rather it is a weather-tight enclosure). The top floor of the reactor building is the service floor from which the refuelling of the reactor is conducted. In both **Figure 4** and **Figure 5** one can observe a large metallic structure held on railings; this is the service floor crane and it is used to assist during refuelling operations. In order to allow access to the reactor to conduct refuelling operations, the steel drywell head (painted in yellow, **Figure 4**) is removed using the crane, and located in a designated area on the service floor as shown in the photographs of Ref. 5. The Reactor Pressure Vessel (RPV) head is then removed.

Spent Fuel Storage

72 The spent fuel strategy in Japan is to store spent fuel safely until it can be reprocessed. This strategy has necessitated increased spent fuel storage capacity at reactor sites, as well as developing a centralised off-site spent fuel store at Mutsu city. Japan is also developing its own reprocessing capability (in addition to reprocessing some of its fuel overseas).

73 On discharge from the reactor spent fuel is placed in the reactor storage pond. These are robust structures that are filled with water to cool the fuel and provide shielding from gamma radiation from within the spent fuel. The ponds are designed with cooling systems to maintain water temperatures around 30°C to 40°C and maintain water levels several metres above the top of the fuel assemblies. After several years the residual decay heat within the fuel has decayed to a level where the spent fuel can be transferred into dry casks for further storage.

74 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 in a building segregated from the reactors which contains around 6000 spent fuel assemblies.
- Spent fuel is also stored on-site in a dry storage facility that contains 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 (Ref. 6).

75 Overall, 60 percent of the spent 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 Power Industry

76 With the exception of Sizewell B, which is a 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. All Magnox reactors having steel pressure vessels were safely shut down at the end of their lives in a phase manner by the end of 2006.

77 The Magnox reactors, started operation between 1956 and 1971. These are carbon dioxide gas-cooled, graphite moderated reactors that use natural (or in some cases very slightly enriched)

uranium fuel in a magnesium alloy cladding. The first nine installations had steel reactor pressure vessels and all these are now permanently closed down. The two remaining stations at Oldbury and Wylfa have pre-stressed concrete reactor pressure vessels. These later designs had significant safety advantages over the steel pressure vessels since that a sudden and unexpected failure of the main pressure vessel boundary is considered virtually impossible.

78 Seven AGR stations were commissioned between 1976 and 1988 each with two reactors. AGRs use enriched uranium oxide fuel in stainless steel cladding. This, together with the pre-stressed concrete pressure vessel, allowed gas outlet temperatures of over 600°C and gas pressures of over 30-40bar[b].

79 The UK's gas-cooled reactors do not need secondary containment. None of the design basis loss of coolant accidents precipitate large scale fuel failure and the plant is designed to be capable of retaining the bulk of any radioactive material that might be released from the fuel. In contrast, containment buildings are required for PWRs and BWRs because a design basis large break loss of coolant accident results in significant fuel failure and release of radioactive fission products. AGRs can run with limited numbers of failed fuel pins.

80 The most recent nuclear power plant to be built in the UK is the PWR at Sizewell B. This became operational in 1995. This reactor uses enriched uranium oxide fuel clad in zircaloy and pressurised water as the coolant.

UK Regulatory Regime

Legal Framework

81 In the UK, the regulatory framework is established by two pieces of legislation: the Health and Safety at Work etc. Act 1974 (HSWA), and the Nuclear Installations Act 1965 (NIA65). Under HSWA, employers are responsible for ensuring, so far as is reasonably practicable, the safety of their workers and the public and this responsibility is reinforced on nuclear sites by the NIA65. The legal regime is complemented by the Ionising Radiations Regulations 1999, which provide for protection of workers in all industries from ionising radiation, and by the generality of health and safety regulation. The regulatory framework for managing the environmental impacts of nuclear sites is established largely by the Environmental Permitting Regulations 2010 in England and Wales and by the Radioactive Substances Act 1993 and other legislation defined under the Environment Act 1985 in Scotland.

Department of Energy and Climate Change (DECC)

82 DECC has a number of policy roles in respect of the nuclear industry. These include responsibility for energy policy generally (including the role of nuclear power), prescribing the activities that should be subject to the nuclear licensing regime, nuclear emergency planning, nuclear security and safeguards, international treaties and the Convention on Nuclear Safety, as well as the international nuclear liability regime. It is also responsible for those parts of the UK civil nuclear industry still owned by the Government.

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[b] 1 bar is approximately equal to 1 atmosphere.

83 In carrying out its responsibilities, DECC will, when appropriate, seek factual information on safety related matters from ONR and advice on environmental issues from the environment agencies.

Office for Nuclear Regulation (ONR)

84 ONR, formerly HSE's Nuclear Directorate, was established as a non-statutory agency of the HSE on 1 April 2011. However, the UK Government's intention is to bring forward legislation to create a new independent statutory body outside of the HSE to regulate the nuclear industry. In addition to nuclear safety, security and safeguards, ONR will take on the relevant functions currently carried out by the Department for Transport (DfT).

85 ONR's regulatory responsibilities are broad, covering nuclear activities from power generation, weapons development, chemicals and research, through to decommissioning.

Technical Support

86 ONR does not use dedicated technical support organisations in the way many other regulators do. Most of the expertise to regulate nuclear safety is available to the regulator through its own inspectors. Where necessary, additional technical support is provided through three main routes:

- From within HSE - the Health and Safety Laboratory provides technical support on a wide range of safety issues that are not specifically related to nuclear installations e.g. ventilation or protective equipment.
- Purchasing, through normal procurement routes, a range of one-off consultancy contracts from a range of suppliers.
- Purchasing consultancy advice through a framework agreement with pre-tendered suppliers.

Environment Agencies

87 The Environment Agency is the principal environmental regulator in England and Wales. Its regulatory responsibilities include the authorisation or permitting of the disposal of radioactive wastes from nuclear licensed sites. It is sponsored by the Department for Environment, Food and Rural Affairs (Defra) and the Welsh Assembly Government (WAG) and works closely with ONR and the DoH on nuclear matters.

88 The Scottish Environment Protection Agency (SEPA) has the equivalent responsibilities in Scotland and is sponsored by the Scottish Government. On radioactive waste matters, it works closely with the Rural and Environment and Public Health Directorates of the Scottish Government.

89 ONR, the Environment Agency and SEPA work closely with one another to ensure the effective co-ordination of their respective regulatory activities at nuclear installations. ONR consults the Environment Agency or SEPA before:

- Granting a nuclear site licence.
- Varying a nuclear site licence if the variation relates to or affects the creation, accumulation or disposal of radioactive waste.

90 In addition to their own routine inspection activities on nuclear licensed sites, the Environment Agency and SEPA carry out planned joint inspections with ONR and co-operate in the investigation of incidents where appropriate.

Health Protection Agency

91 The UK Health Protection Agency (HPA) was established on 1 April 2005 under the Health Protection Agency Act 2004 as a non-departmental public body, replacing the HPA Special Health Authority and the National Radiological Protection Board (NRPB), and with radiation protection as part of health protection incorporated in its remit.

92 The NRPB role continued as the Radiation Protection Division of HPA and, since 1 April 2010, as the Centre for Radiation Chemical and Environmental Hazards (HPA-CRCE). Its statutory functions include:

- The advancement of the acquisition of knowledge about protection from radiation risks.
- The provision of information and advice in relation to the protection of the community (or any part of the community) from radiation risks.

93 HPA-CRCE also provides technical services to persons concerned with radiation hazards; it makes charges for such services and for providing information and advice.

UK Nuclear Emergency Arrangements

94 In the unlikely event of a nuclear emergency in the UK, emergency preparedness and response provides an additional safeguard so that if there was an accidental release of radioactive material, protection could be provided to the public who might be affected. Nuclear emergency arrangements are evolving continually in response to changing circumstances, improved techniques and lessons learnt from emergency exercises and real events. This ensures that any changes necessary can be incorporated as required into the relevant plans and emergency arrangements. Further details are contained in Annex D.

OVERVIEW OF THE FUKUSHIMA ACCIDENT AND KEY FACTORS

Summary

95 The accident at Fukushima is still ongoing and serious. It is likely once the situation on the ground has stabilised and official Japanese and international enquires and investigations report, some of the details below will be clarified, modified or corrected. However, this section represents ONR's current understanding of the sequences of significant events at Fukushima from publicly available sources, predominately press releases by the operator, the Tokyo Electric Power Company (TEPCO), the Japanese nuclear regulator, NISA and the IAEA. Also, the workers on-site will be dealing on a daily basis with significant and serious challenges as they continue to manage the hazards. These have not all been reported here.

96 The earthquake occurred on Friday 11 March 2011 at 2:46pm local time (Ref. 7). The tsunami hit the coastline approximately one hour later. The operating reactors shutdown as designed when the earthquake hit. It is likely that off-site power from the grid was lost at this time but on-site diesel generators started as designed providing AC power to the site (required for both the normal post-trip cooling of the reactors and to provide on-going cooling to the spent fuel ponds). All on-site diesel generation was lost when the tsunami reached the power station. Reports are that it flooded to a depth of up to six metres.

97 Further details and key factors are detailed below.

Timeline of Key Events

98 The earthquake sequence that affected and continues to affect the Fukushima site started with a magnitude 7.3 event on 9 March which was followed by a series of smaller aftershocks. The main shock, of magnitude 9.0 (known as the Tohoku event) occurred on 11 March 2011 at 2:46pm local time. Up until 12 April 2011 there had been 419 aftershocks with a magnitude greater than 5 update with METI presentation. The most important of these were the magnitude 7.1 events on 11 March 2011 and on 7 April 2011. The geographical spread of the aftershocks is large as would be expected following such a large event.

99 The main shock lasted over 90 seconds and was located a depth of around 20 miles, 109 miles East North East of Fukushima. The event resulted from thrust faulting on or near the subduction zone plate boundary between the Pacific and North America plates. At the latitude of this earthquake, the Pacific plate moves approximately westwards with respect to the North America plate at a rate of 83 millimetres/yr, and begins its westward descent beneath Japan at the Japan Trench. Japan has a long history of large earthquakes, however the Tohoku event is the largest to have hit the island, the fifth largest in the past 100 years, and within the list of the largest 10 events in recorded history. The previous largest in Japan were the Great Kanto event (M_L8.3) of 1923 and the Meiji-Sanriku event (M_L8.5) of 1896. Both of these events caused significant damage and large numbers of fatalities.

100 The tsunami resulting from the main shock arrived at the Fukushima-1 site at around 3:41pm local time on 11 March 2011, just under an hour after the earthquake.

Impacts of the Earthquake on the Site

101 The effects on the site were measured in the basements of the six reactor units at between 0.33g[c] and 0.56g peak horizontal acceleration (see **Table 4** below). There is no evidence of any ground rupture on the site or of any liquefaction. The site itself is underlain by a significant depth of mudstone with the reactor buildings founded on material with a shear wave velocity in excess of 600m/sec.

102 On a broader scale, there was an overall downward shift of the coastline elevation by estimates varying between 0.6 and 1.5m.

103 It is clear from **Table 4** below, that the observed horizontal accelerations are broadly of the same order as the basic ground motion claimed in the seismic review of the plants. It is therefore not entirely surprising that there are no reports of significant damage to the main structures as a result of the earthquake itself. It is clear from the limited images available from inside the plant that there was peripheral damage to items such as control room ceilings etc.

104 The Fukushima-1 reactor units are fitted with an automatic shutdown system linked to ground motion instrumentation. The reactor shutdown levels were set at the reactor units at around 0.14g horizontally and around 0.1g vertically (Ref. 8). These levels were encountered early on in the event, and it would appear from available data that the system worked and that shutdown was initiated via the seismic trip.

105 It should also be noted that this is not the first time the plant has been hit by a seismic event. In 1978, the 7.4 magnitude Miyagi earthquake 140km from the plant resulted in site ground accelerations of 0.125g. The damage levels following this event were minimal and the plant was fully operational within a matter of days (Ref. 9).

106 It is known that the Fukushima-1 site is heavily instrumented, however only limited information has been made available as yet.

Impact of the Tsunami on the Site

107 The tsunami arrived at the Fukushima site at around 15:41 local time on 11 March 2011. The site was rapidly inundated to depths up to 6m.

108 Information provided by TEPCO (Ref. 10) relates heights of both the tsunami and the seawall to a level known in Japan as OP (in a similar manner to which Ordnance Survey maps in the UK are referenced to sea level). OP is the baseline level known as the Onahama Port Base Level. The height of the flood protection measures was set at OP+5.7m. The general ground level adjacent to the waters edge is at OP+4m, however the ground level adjacent to the Turbine Building and the reactor building is at OP+10m. The estimated height of the tsunami wave is at about OP+14-15m. The inundation depth adjacent to the reactor buildings and turbine buildings is therefore in the range of 4-5m, but may locally have been up to 6m.

109 The incoming wave completely surrounded the buildings on-site, and entered the buildings via ground level access doors. There are no details as yet over any protection measures that may have been available to prevent or limit the ingress of water into the buildings.

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[c] g denotes the acceleration due to gravity. 1g = 9.81ms^{-2}

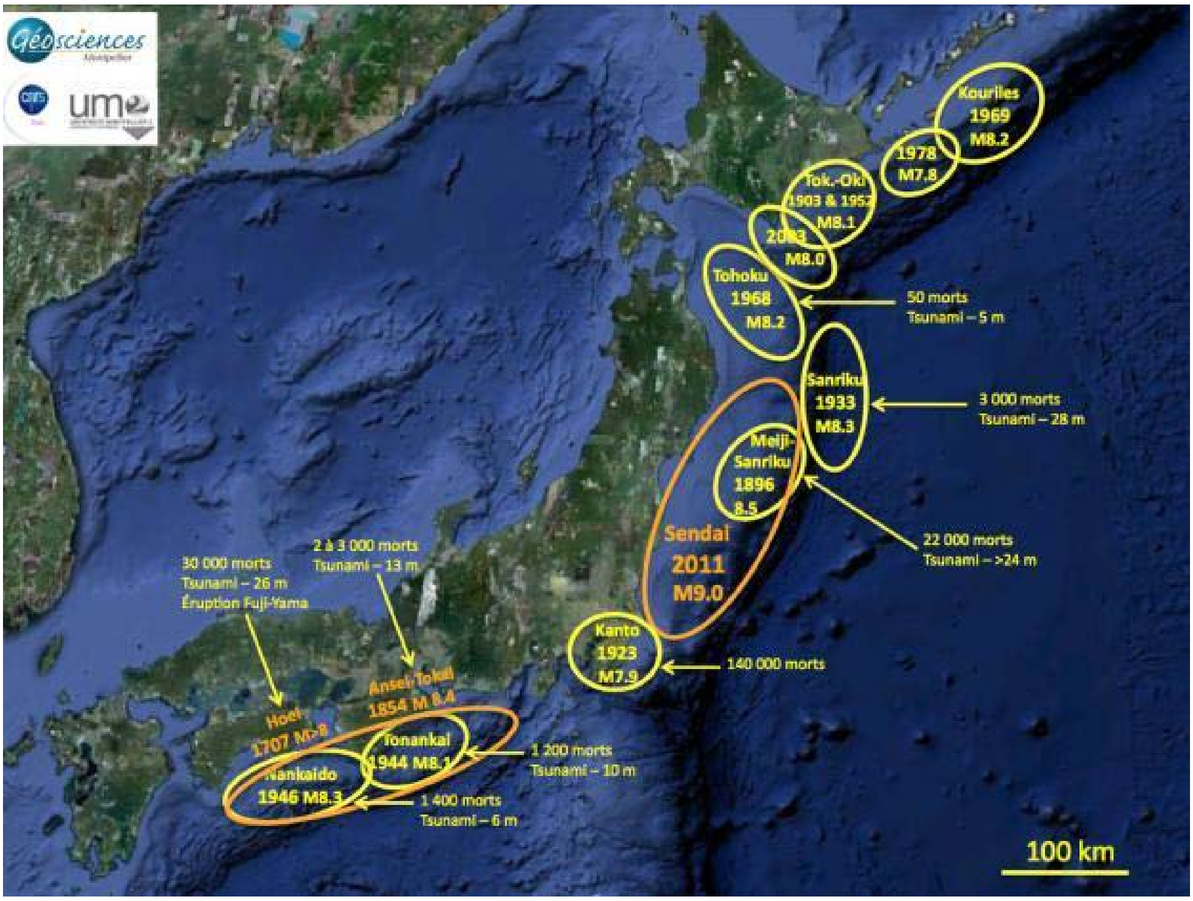
110 The turbine hall and the reactor buildings have significant portions below ground level, and it is fair to assume that considerable volumes of water entered the lower portions of the buildings. The diesel generators and AC switchgear which were located in the lower portions of the turbine hall were inundated and ceased running.

111 Considerable damage was done to ground level structures on the shoreline, including the complete destruction of two large diesel storage tanks to the North of the site. Structures related to the main seawater intake were severely damaged. The site was left littered with debris.

112 The extremely long wavelength of tsunami waves (and consequently period) means that the site remained inundated for a period of between 30 minutes and an hour following the main wave arrival.

113 **Figure 6** below shows the 2011 earthquake and tsunami alongside other recently recorded events off the east coast of Japan.

Figure 6: Earthquake and Tsunami Data for Events off the East Coast of Japan.



Broader Impact on Local Area around the Site

114 The Tohoku earthquake was felt over a significant area of Japan, however the effects were relatively small in terms of damage to engineered structures. In some areas, there was extensive liquefaction, and severe damage to some petrochemical facilities. In addition, there was extensive

disruption to transport systems, both train and roads. Telecommunications were badly affected as a result of direct damage and loss of power systems.

115 The tsunami was more disruptive than the earthquake, with inundation reaching many kilometres inland and affecting an area of up to 500km^2. The buildings and infrastructure of many towns and villages have been completely destroyed, with debris scattered over a large area. This, combined with the earthquake damage created significant problems in the first few days following the events for access to the Fukushima-1 site for specialist equipment and personnel.

Reactor Units 1, 2 and 3

116 Reactor Units 1, 2 and 3 were operating at power when the earthquake struck while the Reactor Units 4, 5 and 6 were already shutdown. Reactor Unit 4's fuel had been off-loaded to its pond, while Reactor Units 5 and 6 had a full complement of fuel in their respective reactor pressure vessels despite being shutdown. The inventory in the respective ponds is shown below, taken from Ref. 1:

Table 3: Number of Fuel Assemblies in Cooling Ponds at Fukushima-1

Unit	Capacity	Irradiated Fuel Assemblies	Unirradiated (new) Fuel Assemblies	Most Recent Additions of Irradiated Fuel
1	900	292	100	March 2010
2	1240	587	28	September 2010
3	1220	514	52	June 2010
4	1590	1331	204	November 2010
5	1590	946	48	January 2011
6	1770	876	64	August 2010

117 Despite the loss of power, the reactors at the Fukushima-1 site had a number of ways to provide cooling for a short period time following the tsunami. These systems described in more detail below required no AC power, plant service and instrument air, or external cooling systems to deliver their function (Ref. 12). However, they did require DC battery power to operate. It is believed that the batteries were only rated for 8 hours which was an insufficient time for this event for alternative power sources to be restored.

118 NISA states that TEPCO formally reported to them the "Inability of water injection of the Emergency Core Cooling System" for Reactor Units 1 and 2 at 4:36pm local time on 11 March 2011 and at 5:10am local time on 13 March 2011 for Reactor Unit 3 (Ref. 13). Following the loss of emergency cooling/injection into the previously operating reactors, NISA reported the following sequence of key events over the subsequent few days (Ref. 13):

Reactor Unit 1

- Containment venting started at 10:17am local time on 12 March 2011.
- Hydrogen explosion in the upper structure at 3:36pm local time on 12 March 2011.
- Sea-water injection into the reactor pressure vessel at 8:20pm local time on 12 March 2011.
- Sea-water injection stopped due to lack of water at 1:10am local time local time on 14 March 2011. Restarted several hours later.

Reactor Unit 2

- Containment venting started at 11:00am local time on 13 March 2011.
- Blowout panel opened in reactor building following explosion in Unit 3 at 11:00am local time on 14 March 2011.
- Sea-water injection into the reactor pressure vessel at 4:34pm local time on 14 March 2011.
- Reactor vented at 0:02am local time on 15 March 2011.
- Explosion heard and suppression chamber/torus pressure decreased at 6:20am local time on 15 March 2011. Containment assumed to be damaged from this point.

Reactor Unit 3

- Containment venting started at 8:41am local time on 13 March 2011.
- Sea-water injection into the reactor pressure vessel at 11:55am local time on 13 March 2011.
- Sea-water injection stopped due to lack of water at 1:10am local time on 14 March 2011. Restarted several hours later.
- Reactor vented at 5:20am local time on 14 March 2011.
- Containment vessel pressure rose at 7:52am local time on 14 March 2011 ahead of a large (presumed hydrogen) explosion at 11:01am local time.

119 NISA press releases suggest that the initial sea-water injection through the "*Fire Extinguish Line*" was limited to about 2m^3/hr. Without active cooling and/or sufficient water injection, the reactor fuel elements in the cores would have become uncovered, over-heat, lose their geometry and integrity, and release radioactive gases and particles previously contained by the zircaloy fuel cladding. In addition, once zircaloy is no longer covered with water but is in a hot steam atmosphere, hydrogen can be produced with the resulting explosion risk. Indications of the water level in the reactor pressure vessel reported since 15 March 2011 indicate that the fuel in Reactor Units 1 to 3 has consistently been only half to two thirds covered (Ref. 14, IAEA fax to authorities, 15 March 2011 at 5:40pm local time). The hydrogen explosions from 12 March 2011 indicate that the fuel was actually uncovered much earlier than 15 March 2011.

120 Sea-water injection was not increased from 2m^3/hr until 23 March 2011 (Reactor Unit 1) and not replaced with freshwater until 25 March 2011 (Ref. 13). Pumps on fire trucks were initially used for the water injection. Pumping started to be switched to temporary motor driven pumps from 27 March 2011 (Reactor Unit 1 from 29 March 2011, Unit 2 from 27 March 2011 and Unit 3 from 28 March 2011).

121 To mitigate the risk of a further hydrogen explosion in Reactor Unit 1, TEPCO started to inject nitrogen into the containment vessel from 7 April 2011 (Ref. 13).

122 At the time of writing, the reactors appear to remain in a steady state with a constant supply of freshwater injection into their reactor cores. However there is currently no active closed loop cooling of the reactors and they have not reached a stable state, usually described as “cold shutdown”. There is no definitive information on the condition, geometry or location of the fuel in the reactor cores, other than the demonstrable generation of hydrogen in the first few days of the accident.

123 All the indications suggest that the containment structure surrounding Reactor Unit 1’s reactor pressure vessel remains largely intact. Pressure measurements from Reactor Unit 2 are being treated cautiously by NISA and IAEA but it is assumed that the containment suffered damage in the explosion on 15 March 2011. The status of Reactor Unit 3’s containment vessel is less clear but photographs such as the one below show that the damage to the surrounding building caused by the explosion of 14 March 2011 was extensive.

Figure 7: Post Accident Photograph of Reactor Units 1-4 at Fukushima-1

Reactor Unit 1 to 4 Fuel Ponds

124 It is not known whether the structures of the fuel ponds were significantly damaged during the initial earthquake resulting in a loss of water inventory. However in the absence of any active cooling of the ponds following the loss of the power that occurred with the tsunami, the water temperature in the ponds would have inevitably increased, resulting in water loss first through evaporation and then more rapidly through boiling if the temperatures reached 100°C. While the

spent fuel remains covered, even if the water was boiling, the threat from the Fukushima-1 site ponds would have been small. However, once uncovered, it is unlikely that the fuel will be cooled sufficiently to prevent it from becoming damaged and releasing contained volatile isotopes. Fuel exposure will result in the following issues:

- A significant increase in gamma radiation in the vicinity of the ponds because of loss of shielding from the loss of water.
- Oxidation of the zirconium cladding exposed to air, resulting in hydrogen generation and possible risk of explosion in a similar scenario to that which could occur in the reactors.
- If completely drained of water, the temperatures in the ponds could be high enough for the zirconium cladding to ignite resulting in a zirconium fire. A fire in the spent fuel ponds would be expected to release a significant amount of activity to the environment, especially from those reactor ponds that had suffered damage to the building cladding.

125 Under normal circumstances the operators would have many days or even weeks to add water, but it is clear that the ponds at the Fukushima-1 reactor units were considered a significant threat within a much shorter timescale.

126 The last temperature reading from Reactor Unit 4's pond was 84°C at 4:08am local time on 14 March 2011 (Ref. 15). This pond had the highest heat loading because all the fuel in its reactor had been fully offloaded into it, adding to the normal inventory of spent fuel stored in there (see **Table 3**). It is believed that the Reactor Unit 4 reactor building (including the pond) suffered damage from the Reactor Unit 3 explosion which occurred at 11:01am local time on 14 March 2011. At approximately 6:00am local time on 15 March 2011 TEPCO confirmed an explosive sound and damage around the 5th floor rooftop area of the reactor building (Ref. 16). It is reasonable speculation to assume that the structures associated with pond suffered additional damage by either or both of these explosions beyond any caused by the initial earthquake, creating further mechanisms by which water inventory could be lost from the pond. Fires were reported in Reactor Unit 4 on 15 and 16 March 2011 but there is no definitive information available to say that these were spent fuel fires (zirconium burns with a light grey smoke) or were attributable to another source in the vicinity of the pond.

127 It is expected that future investigations will establish that Reactor Unit 3's pond also suffered mechanical damage in the explosion of 14 March 2011. No temperature data from Reactor Unit 3's pond has been published. However, immediately prior to the explosion it is assumed that the Reactor Unit 3 pond was in a less perilous state because it only had approximately 40 percent of the fuel assemblies Reactor Unit 4 had, and they had been cooled longer since its refuelling outage.

128 TEPCO started spraying Reactor Unit 3's pond with water cannon from the ground on the evening of 17 March 2011, having tried to add water via helicopters earlier in the day. Spraying of Reactor Unit 4's pond commenced with water cannon from 20 March 2011. Water cannon/fire trucks were replaced on Reactor Unit 4 with water spray from above via the articulated arm of a concrete pumping truck from 22 March 2011 (Ref. 13). This concrete pumping truck, capable of supplying 50 tonnes of water per hour was subsequently also rotated around Reactor Unit 1 (from 31 March 2011) and Reactor Unit 3 (from 29 March 2011) for a few hours at a time at each unit.

129 NISA has not released any information on the effectiveness of the water injection to the fuel ponds in Reactor Units 1, 3 and 4 in terms of the water level or temperatures. It is known that much more water has been directed towards the ponds (Reactor Units 3 and 4 especially) than their capacity.

130 NISA state that sea-water injection to Reactor Unit 2's pond first commenced on 20 March 2011 (the method is not clear). Injection switched to spent fuel pool cooling line from 25 March 2011 (the cooling line was only providing makeup water and not active cooling). Temperature readings from Reactor Unit 2 started to become available from 21 March 2011, showing water temperatures generally around 50°C although temperatures have risen occasionally to around 70°C before dropping again in subsequent days.

131 Significant levels of iodine-131 and caesium-137 have been detected at sampling points away from the Fukushimi-1 site. While caesium-137 will be released from uncovered and damaged spent fuel in the ponds, iodine-131 generated during power operations while the fuel is in the reactor core will fall away with a half life of eight days, such that after several weeks of cooling in the ponds there should be little remaining. The high amounts of iodine-131 found suggests that the radiological consequences from the Fukushima-1 site due to airborne releases has so far been dominated by the releases from the reactors and not from the fuel ponds, although the ponds presented a considerable threat given that there was no containment to prevent a release.

Reactor Units 5 and 6

132 Both Reactor Units 5 and 6 were shutdown at the time of the earthquake. They are located slightly away from Reactor Units 1 to 4 and appear to have suffered less damage. However, with the total loss of power on-site and subsequent loss of active cooling, the temperatures in the reactors and ponds inevitably started to rise.

133 On 17 March 2011 operators were able to start one of the Reactor Unit 6's diesel generators. This initially facilitated water injection to the reactor pressure vessel and the fuel ponds through the Makeup Water Condensate System (Ref. 13). On 19 March 2011, workers successfully connected the second diesel generator on Reactor Unit 6. The two generators were used to power active cooling systems on both reactor units. Reactor Unit 5's reactor was declared to be in cold shutdown at 2:30pm local time on 20 March 2011, with Reactor Unit 6 declaring the same condition three hours later. The fuel pond temperatures also rapidly returned to acceptable levels (Ref. 11).

134 Power supplies were switched from emergency diesel generators to the restored external power supply to Reactor Units 5 and 6 on 21 and 22 March 2011 respectively (Ref. 13).

Restoration of Off-site Power

135 When a nuclear power station is operating, it generates its own electricity to power its essential systems and services. However once it is shutdown, it is reliant on either the grid or on-site emergency diesel generators or other reactors at site for AC power. The connection to the grid was lost during the initial earthquake and the subsequent tsunami resulted in a loss of all the emergency diesel generators and all reactors shutdown. TEPCO therefore expended a significant amount of effort to restore power on-site through a reestablishment of a grid connection.

136 The following key events have been identified in NISA briefings (Ref. 13) for Reactor Units 1 to 4:

- Reactor Unit 1 – Lighting recovered in central control room at 11:30am local time on 24 March 2011. Reactor Pressure Vessel (RPV) injection switched to off-site power at 12:12pm local time on 3 April 2011.
- Reactor Unit 2 – Power centre received power at 3:46pm local time on 20 March 2011. Lighting in Central Operation Room established at 4:46pm local time on 26 March 2011. RPV injection switched to off-site power at 12:12pm local time on 3 April 2011.
- Reactor Unit 3 – Partial lighting in turbine hall on 2 April 2011. RPV injection switched to off-site power at 12:18pm local time on 3 April 2011.
- Reactor Unit 4 – Power Centre received power at 10:35am local time on 22 March 2011.

Common Spent Fuel Pond

137 There was very little information published on the status of the common spent fuel pond immediately following the earthquake. It was reported on 18 March 2011 that the fuel in the pond was covered by water and on 19 March 2011 the water temperature was stated to be 57°C (Ref. 17). Water spray was supplied over the pond for a few hours on 21 March 2011. Power was supplied to the building on 24 March 2011 allowing cooling to be restarted the same day (Ref. 13). This rapidly brought the temperatures down to normal levels.

Dry Casking Facility

138 There have been no reports available to us of problems with the dry casking facilities. Dry casks are normally more passively safe than fuel ponds.

Role and Relevance of Key Reactor Systems during the Fukushima Accident

139 All the Fukushima-1 reactor units were based on the concept of defence in depth and had multiple systems to prevent and mitigate accident scenarios. From the description of the events above, it is apparent that some of these systems worked as planned, some only partially and others were made ineffective by the earthquake and subsequent tsunami. This section provides an overview of the key systems available on the Fukushima-1 BWRs and comments on how they have performed based on the information available.

140 In general, the information regarding BWR technology provided has been extracted from publicly available information Refs 18, 19 and 20. Although this is sufficient at this stage, it is acknowledged that there are gaps in our knowledge of the BWR technology, of the specific characteristics of the Fukushima-1 reactor units and of the specific events that occurred during the evolution of the accident sequences.

141 Additional information will be sought and knowledge gaps will be filled, as far as possible, so that we will be in a position to present more precise and complete information in the final report.

Control

142 BWRs are unique in that the control rods used to control the rate of nuclear fission and to shutdown the reactor (to stop the chain reaction) are inserted from the bottom of the reactor

vessel by a high-pressure hydraulically operated system. The control rod system is the primary fast way to shutdown the BWR reactors. It is believed that the control rod systems actuated automatically successfully in all the Fukushima-1 reactor units that were in operation at the time of the Tohoku earthquake (Reactor Units 1, 2 and 3) since no failures were reported. The penetration of the control rods through the bottom of the Reactor Pressure Vessel (RPV) may act as a particular route for material to escape from the core under severe accident conditions.

143 BWRs have a diverse system to shutdown the reactor called standby liquid control system. This system injects a “neutron poison” (boron) into the reactor vessel to shutdown the chain reaction, independent of the control rods, and maintains the reactor shutdown as the plant is cooled down. The standby liquid control system consists of a storage tank, two positive displacement pumps, two so-called squib valves, and the piping necessary to inject the neutron absorbing solution into the reactor vessel. The standby liquid control system is manually initiated and provides the operator with a diverse, but relatively slow, method of achieving reactor shutdown conditions. Extra boron was shipped to Japan in response to the accident as a precaution and boronated water was added to the reactor at some stage.

Post-trip Cooling

144 When a nuclear reactor shuts down, the nuclear reaction stops but the core still continues to generate decay heat, for example, a 500MW(E) (i.e. electrical power) reactor will still generate over 5MW(T) (i.e. thermal power) after a day (equivalent to approximately 2500 2kW electrical fires). This decay heat decreases very quickly initially and then slower and needs to be removed to avoid the reactor core to overheat. In general, the decay heat is removed by bypassing the turbine and dumping the steam directly to the condenser. The condensed water is pumped back into the reactor. This process reduces both the temperature and the pressure in the reactor vessel.

145 The shutdown cooling mode of the Residual Heat Removal (RHR) system is used to complete the cool down process when the pressure in the reactor vessel decreases to a value low enough for the RHR pumps to work properly. In the RHR mode, water is suctioned from the reactor via one of the reactor recirculation loops; it is then passed through a heat exchanger to cool down, and returned back to the reactor via the recirculation loop. The RHR heat exchangers are cooled by a separate system which is part of the installation’s heat sink. All the RHR pumps as well as the pumps in the cooling systems require AC power supply to operate. As long as the systems are operating properly and the power supply is available, the RHR cooling mode can be maintained indefinitely.

146 Because of the sequence of events on 11 March 2011, none of Fukushima-1 Reactor Units 1, 2 or 3 were able to achieve conditions for RHR cooling. The main reason was the unavailability of AC power. It also believed that following the loss of off-site power the main steam lines may have isolated automatically, in which case bypassing the turbine and cooling with the condenser was not an option, and the other systems available were not able to complete the cooling process.

147 In contrast to Reactor Units 1 to 3, at the time of the event, the temperatures in the reactors in Units 5 and 6 were already low because they had been shut down for a long time and the decay heat was already very low. It is expected that the reactors were being cooled in RHR mode when the Tohoku earthquake occurred. Because of this, and although it appears that the temperatures in these two reactors did increase following the Tohoku earthquake, the increases were not sufficient to cause damages to the reactor cores. These reactors were returned to a situation called “cold shutdown” on 20 March 2011 and have remained in that state since.

148 As Reactor Unit 4 had been defueled to its pond, there were no requirements for post-trip cooling and is not discussed further.

Reactor Isolation and Pressure Control

149 A TEPCO press release on 12 March 2011 at 00:00am local time (Ref. 21) indicated that the main steam isolation valves in Reactor Units 1 to 3 were closed. It is believed that isolation of the steam lines may have occurred as a consequence of the detection of a loss of off-site power but this will need to be confirmed. In the event the reactor becomes isolated from its heat sink some systems must control the reactor inventory and pressure. In Fukushima-1 Reactor Unit 1 BWR-3 model both functions, i.e. pressure and inventory control, are carried out by a single system called the Isolation Condenser. This system is discussed below.

150 All BWR plants have Safety Relief Valves (SRV) to provide overpressure protection. The steam released gets discharged into the suppression pool where it is condensed. This can raise the temperature of the suppression pool.

151 Reactors Units 1 to 6 have an Automatic Depressurisation System (ADS). The ADS consists of a number of automatically activated relief valves that depressurise the reactor vessel (normally to allow actuation of the low-pressure injection systems). The ADS valves open upon receipt of a “very low reactor level” signal or a “high drywell pressure signal”. It is expected that ADS valves can also be actuated manually. ADS valves discharge into the suppression pool.

152 We have not been able to find in the reports made by TEPCO and IAEA any specific information about any attempts made by the operators to depressurise the reactor vessels. Therefore, we do not know yet whether the ADS played any role in the evolution of the events at Fukushima-1 Reactor Units 1 to 3.

Semi-Passive Reactor Cooling Systems

The Isolation Condenser

153 From Refs 21 and 22 and others, it appears clear that following the Tohoku earthquake Fukushima-1 Reactor Unit 1 was initially cooled with an Isolation Condenser.

154 The Isolation Condenser is a passive high-pressure system that is on standby during normal operation. This system is able to remove decay heat when the reactor is shutdown and isolated from the turbine. The system is designed to start automatically upon receipt of a “high reactor pressure” signal; it can also be activated manually by the operators.

155 The Isolation Condenser operates by natural circulation (i.e. without pumps). During its operation, steam flows from the reactor, condenses in the tubes of the Isolation Condenser and returns by gravity to the reactor. For the Isolation Condenser to operate, a number of valves need to change position. It is believed, but has not been confirmed, that these actuations may require DC power supply that can be provided by batteries.

156 The water in the outside of the tubes will heat-up, and eventually boil and vent steam to the atmosphere. Cold make-up water can be provided from various sources to fill-up the Isolation Condenser. Without adding more water, the Isolation Condenser will empty, and its cooling capability will stop, in probably no more than 1.5hrs.

The High Pressure Coolant Injection System

157 Fukushima-1 Reactor Unit 1 was also equipped with a system to inject water in the reactor at high pressure, powered by battery supply, called the High Pressure Coolant Injection (HPCI) system. Refs 19 and 22.

158 Under reactor isolation conditions, the HPCI is a back-up system for the Isolation Condenser in the early BWR-3s and for the Reactor Core Isolation Cooling (RCIC) system (described below) for the BWR-4s.

159 The HPCI does not require AC power, instrument air or external cooling to perform its function.

160 The HPCI consists of a turbine driven pump, auxiliary systems required for turbine operation (including DC power that can be provided by batteries) and associated piping and instrumentation. This system is normally aligned to suction water from the condensate storage tank, the suppression pool being an alternate source of water. According to Ref. 23 the water in the condensate storage tank may last for more than eight hours although details about the capacity of these tanks at the Fukushima-1 reactor units have not been found readily available yet.

161 The HPCI is designed to start automatically on receipt of a low water level in the reactor signal, or a high drywell pressure signal. It can also be actuated manually by the operators. The steam used by the turbine is discharged into the suppression pool.

162 Reactor Unit 1’s HPCI may have been inoperable because the battery was soaked in water Ref. 22. However, it is not clear when the system stopped injecting water or if it ever did. Fukushima-1 Reactor Units 2 and 3 were also equipped with HPCI systems (Ref. 24) and it is believed that the system operated for some time in Reactor Unit 3 (Refs 21 and 22). It has not been possible to establish whether the Reactor Unit 2 HPCI was operable at all.

The Reactor Core Isolation Cooling System

163 Both Fukushima-1 Reactor Units 2 and 3 were equipped with a further cooling system, the Reactor Core Isolation Cooling (RCIC) System. From a TEPCO press release on 12 March 2011 at 5:00am local time (Ref. 21) it is believed that this system operated in both reactors for a number of hours after the Tohoku earthquake. Ref. 22 gives confirmation of this.

164 The function of the RCIC system is to provide core-cooling make up water to the reactor vessel when it is isolated. The system consists of a steam turbine driven pump capable of delivering water to the reactor vessel at high pressure. Operation of the RCIC is fully automatic or manual. The system is designed to start automatically upon receipt of a “low water level in the reactor” signal. Once the reactor water level is recovered, the system is designed to stop automatically.

165 As with the HPCI, the RCIC system is normally aligned to suction from the condensate storage tank (see above). An alternate source of water for this system is the suppression pool.

166 The RCIC turbine is driven by steam produced in the reactor vessel, and exhausts to the suppression pool under water. It is understood that DC electrical supply is necessary for the control of the turbine and the system flow.

Discussion on the Performance of Cooling Systems

167 The exact causes for the RCIC and HPCI eventually stopping in Reactor Units 2 and 3 are not yet known. However, it could be due to depletion of the batteries or failure of the pumps due to high

temperature in the vicinity of the turbines, or saturation of the water in the suppression pool, but there could be other reasons. A report on station blackout in the USA states: "it is expected that RCIC turbine would be operated only intermittently during station blackout while the HPCI system would serve only as a back-up in the event of RCIC system failure" (Ref. 23, Section 8.1). While this may be so, it is unclear whether the Fukushima-1 operators may have taken any actions to extend the operation time of the HPCI and RCIC pumps which appeared to be surprisingly long (Ref. 25). In addition, Ref. 23, Section 8.1 discusses possible actions that can be taken by the operators to extend availability such as intermittent operation of HPCI versus RCIC to mitigate local temperature rises near to the turbines.

168 BWRs are equipped with additional systems to cool the reactor after the reactor is shutdown. BWR-3s and BWR-4s typically have a core spray system and a Low Pressure Coolant Injection (LPCI) system which has a variety of cooling functions for the reactor, the suppression pool and the containment. These systems are low-pressure systems requiring AC power and were not therefore available to the operators to prevent the situation in Reactor Units 1 to 3 escalating.

Containment Pressure Control

169 In the Mark I containment of Fukushima Reactor Units 1 to 4 there are vacuum relief mechanisms (vacuum breakers) which maintain the balance of the pressures between the drywell and the suppression pool, and protect the containment against excess external pressure:

- The first of these systems consists of a number of valves that vent the suppression pool to the drywell when the pressure in the suppression pool exceeds the pressure in the drywell by a pre-determined value. This system does not require any power supply.
- The second vacuum relief system consists of two vacuum relief lines that vent air from the secondary containment to the suppression pool when the pressure in the secondary containment exceeds the pressure in the suppression pool by a pre-determined value.

170 It is not known whether the vacuum breakers were actuated or played any role during the accident.

171 Cooling of the suppression pool provides the heat removal path from the containment and the reactor when the main steam lines are isolated and the condenser and Isolation Condenser (if present) are both unavailable. Suppression pool water would continue to increase in temperature if heat is not removed from the containment. This would cause an increase in the pressure of steam, leading to a steady increase in the containment pressure. Suppression pool cooling is provided by the Low Pressure Coolant Injection (LPCI) system in its Residual Heat Removal (RHR) mode. In this mode, suppression pool heat is removed via the RHR heat exchangers causing primary containment temperature and pressure to decrease. The containment spray mode of the LPCI system can be initiated, when necessary, to spray cooled suppression pool water into the drywell or suppression pool atmospheres to control primary containment pressure. As mentioned in the previous sub-section, the LPCI system requires AC power and therefore none of its containment cooling functions discussed here were available for the Fukushima-1 Reactor Units 1 to 3. It appears that other means to cool the drywell may have been implemented at the Japanese BWR's as severe accident mitigation features (Ref. 24). However, it has not been possible to find out whether these systems were available or played any role in the events that started on 11 March 2011 at Fukushima-1 Reactor Units 1 to 3. From the information reported it appears that the only solution available to relieve high pressure from the primary containments in Reactor Units 1 to 3 might have been to vent the containment vessels.

172 In September 1989, the United States Nuclear Regulatory Commission (US NRC) issued Generic Letter 89-16 (Ref. 26) requesting all (US) holders of operating licenses for nuclear power reactors with Mark I containments to consider the installation of a hardened wet well (suppression pool) vent. NRC staff believed that the available information at the time provided strong incentive for installation of a hardened vent because of the following:

- All affected plants had in place emergency procedures directing the operator to vent the suppression pool atmosphere under certain circumstances to avoid exceeding the primary containment pressure limit.
- The pre-existing suppression pool venting capability (non-pressure-bearing vent path) could hinder access to vital plant areas or other equipment. This was seen as an unnecessary complication that could threaten accident management strategies.
- Implementation of reliable venting capability and procedures could reduce the likelihood of core melt from accident initiators such as station blackout.
- A reliable suppression pool vent would provide pressure relief through a path with significant scrubbing of fission products resulting in lower releases.

173 According to Ref. 24, in 1992 Japan's Nuclear Safety Commission, which was the nuclear regulatory body at that time, issued a letter entitled "Accident Management as a Measure against Severe Accidents at Power Generating Light Water Reactors" recommending Nuclear Power Plant (NPP) operators to introduce severe accident management measures at their installations. It seems that Japanese utilities completed implementation of severe accident management measures in 2002. Ref. 24 discusses various severe accident measures and their perceived impact (in reducing the risks). From Ref. 24 it is understood that hard vent had been implemented in the relevant Japanese BWR plants.

174 At the time of writing this report there has not been sufficient time to explore the design details of the primary containment vent. It seems that the system vents the atmosphere of the suppression pool to the environment via the stack; that being the case, and considering where the various hydrogen explosions appeared to have occurred, it has not been possible yet to establish what means the Fukushima-1 operators used to vent the atmosphere of the Reactor Units 1, 2 and 3 primary containment vessels.

Hydrogen Control in Mark I and Mark II Containments

175 The possibility of hydrogen gas being produced in accident sequences following the loss of cooling of the reactor core is well known and BWRs have been designed cognisant of such scenarios. In the Mark I and Mark II containment designs protection against combustion of hydrogen generated in the course of some events is accomplished in the short term by inerting the primary containment with nitrogen gas during normal plant operation. The nitrogen gas is used to displace the oxygen in the air and to prevent an explosive mixture of hydrogen and oxygen within the primary containment.

176 In the long-term, hydrogen control is accomplished by adding additional nitrogen gas, using a system called containment atmosphere dilution system, and venting the primary containment via the standby gas treatment system.

177 It is not known how effective or what role the above strategies/systems played in the progression of the accident sequences. It appears that the hydrogen explosions in Reactor Units 1 and 3 were outside the primary containments. In the current recovery phase, TEPCO's strategy is to resume

the active injection of nitrogen where possible into the containments to minimise the risks of further explosions.

Spent Fuel Pond Factors the Fukushima accident

178 The challenges to the safe storage of spent fuel arose from three sources:

1 The loss of pond water cooling and top up capability. This was especially acute in reactor pond 4 which contained over 1300 irradiated fuel assemblies (around 2.5 cores worth), including a recent core off load from November 2010. The pond will have had the largest decay heat loading of any of the reactor storage ponds.

2 Structural damage to the reactor ponds and containment. The condition of the ponds is unknown, but the need for urgent action early in the event timeline might suggest damage to the ponds or pipes and loss of water. The proximity of the ponds just above the reactors increases the risk of pond degradation and loss of systems. The damage to the outer structure around the fuel ponds and handling areas provides a direct escape route to the environment for any activity released from the spent fuel. It is likely that debris resulting from damage to the building has fallen into the storage ponds, and this may have created local blockages in the fuel storage racks leading to local overheating. However, one positive thing arising from the damage to the outer containment is that it did simplify the process of introducing sea-water into the plant either via helicopter or spray. The situation of the large fuelling crane used to off load fuel is not known.

3 The effects of the earthquake on the spent fuel are not known, but it is likely that the fuel was violently shaken resulting in impacts between the fuel assemblies and the storage racks, and with the pond walls. Fuel rods may have been significantly damaged during this event. Storage racks may have been distorted and their spatial arrangement changed possibly eroding margins to criticality safety. Building debris falling into the ponds may block the water cooling pathways in the fuel leading to local overheating.

179 There was a lot of spent fuel in the ponds. In March 2010 it was reported that the storage facilities on-site were 84 percent full, although most of this was in the common pool which appears to have been unaffected.

180 The site had recently moved to high-density storage racks which further increased the heat loading in the ponds (particularly in reactor 4 pond which contained 2.5 cores worth of fuel).

181 It is easy to speculate on what did or did not happen to the spent fuel during the Fukushima accident, however it may be some time until it is known what really happened. However, one of the root causes was decay heat generation within the spent fuel. In the longer term it may be worthwhile to review the cumulative effects of those factors that may have increased decay heat loading in the fuel above design, in the pond (e.g. accumulations of significant amounts of spent fuel, high density storage racks) alongside the robustness of the pond structures water management systems and the adequacy of the original pond cooling system designs.

182 The spent fuel storage ponds are massive concrete and steel structures which are designed to withstand natural hazards. It is not clear what seismic criteria were applied to the design of the storage ponds, but these may have been less than the massive earthquake that was experienced in Japan on 11 March 2011. It is likely that data from the Fukushima accident may allow a good comparison between design criteria and real plant behaviour during significant seismic events.

183 The possibility of a zirconium fire in the spent fuel storage pools was discussed within ONR and with other nuclear regulators around the world. There does not appear to be a general consensus on the conditions required to cause ignition, or the amount of cooling time that the spent fuel requires to eliminate the possibility of ignition.

184 It is not clear if any significant releases of radioactivity occurred from the storage ponds. However, the fact that the operators undertook a number of difficult and dangerous tasks to deliver sea water to the storage ponds of Reactor Units 1 to 4 indicates that they were concerned about such an event happening. It is likely that these actions prevented further escalation and radioactivity release during the Fukushima accident. The decision to use sea-water was inevitable given the seriousness of the situation and the lack of fresh water supplies. The build up of salt depositions in the storage ponds is likely to have a limited effect given that neither the fuel nor the facilities will be operated in the future. Overall it is considered that the use of sea-water (and more recently freshwater) was essential in preventing a significant escalation of the Fukushima accident.

Protection of Fukushima-1 Reactor Units against Natural Hazards and the Impact of the Events

Seismic Design

185 The nuclear power stations at Fukushima were designed and built over a long period of time from 1960 to 1979. Reactor Units 1 to 5 have a BWR type 1 containment (commonly known as a light bulb), with Reactor Unit 6 having a type 2 containment (commonly known as an over/under containment). We will focus on Reactor Units 1 to 4 when considering the design approach.

186 Reactor Unit 1 was originally designed against seismic loading by the reactor supplier General Electric, via a subcontract to the company URS John Blume. It is understood the design basis for Reactor Unit 1 was a peak ground acceleration of 0.18g, although this has yet to be verified (Ref. 9). It is unclear at this stage what the design basis was for the remaining units. The actual design codes used in the design of the civil structures and for the qualification of plant and equipment are not clear. It is reasonable to assume that for Reactor Unit 1, they were American based codes, extant during the design phase (1960-64). Later designs may have been to a mixture of Japanese specific codes and American codes. The Japanese code on seismic design of nuclear facilities (Ref. 27) was first published in 1970.

187 The current Japanese regulatory requirements against seismic loading are detailed in the Nuclear Safety commission regulatory guide for reviewing the seismic design of nuclear power reactor facilities (Ref. 8). Detailed technical guidance is in JEAG 4601 (Ref. 27). These approaches were updated in 2006, and the following statement was provided in the submission to the Convention on Nuclear Safety (CNS) in 2007 (Ref. 29).

> *"The Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities to new nuclear reactors was revised by the Nuclear Safety Commission on September 19, 2006. It requires a higher level of seismic safety resulting from the alteration of the formulation and evaluation method of earthquake ground motion etc. NISA, deciding that the seismic safety should be checked based on the new Guide for the existing nuclear installations, instructed the operators (the licensees of all the nuclear power reactors) to conduct the seismic safety evaluation and to report the results to on September 20, 2006."*

188 The approach in the most recent version of JEAG 4601 (Ref. 27) is to define two levels of event. The highest level is that which the highest safety category plant and equipment must retain functionality against, termed S_s. The second level, termed S_d is a level against which essentially elastic behaviour must be guaranteed.

189 We have not seen the detailed response referred to in Japan's 2007 submission to the Convention on Nuclear Safety (Ref. 29), however TEPCO provided a short press briefing (Ref. 8), which gave some indication of the basic earthquake ground motion S_s for the Fukushima-1 plant according to the guidelines in Ref. 27. In addition, they provided the measured levels of acceleration in the basements of all of the units at the Fukushima-1 site. The table below summarises those results.

Table 4: Summary of the Observed Accelerations and the Basic Earthquake Ground Motion for the Fukushima-1 Site

Fukushima-1	**Observed Data in Basements (g)**		**Earthquake Ground Motion S_s (g) (from JEAG 4601)**	
	Horizontal	**Vertical**	**Horizontal**	**Vertical**
Unit 1	0.47	0.26	0.50	0.42
Unit 2	0.56	0.31	0.46	0.43
Unit 3	0.52	0.24	0.46	0.44
Unit 4	0.33	0.2	0.46	0.43
Unit 5	0.56	0.26	0.46	0.44
Unit 6	0.45	0.25	0.46	0.42

190 As can be seen, the observed values of horizontal acceleration are broadly similar to or exceed slightly the functionality values, and those for vertical acceleration are less than the functionality values.

191 A detailed review of the approach to defining the seismic hazard has not been possible to date. It appears from a review of Ref. 28 that there is no requirement to link the design basis event directly to a frequency of occurrence, rather that a deterministic approach is used. This would then appear to be assigned some exceedance frequency to allow risk values to be estimated. It should be noted that these comments are slightly speculative in nature as the full highly technical document has not been reviewed yet.

Design against Flooding

192 It has not been possible to identify the regulatory requirements in Japan for carrying out flood risk assessments. It is understood however that the tsunami risk is addressed using a publication by the Japanese Society for Civil Engineers (Ref. 30). This document has not been reviewed in detail. However, it appears that tsunami from both near-field and far-field sources are considered. It does not appear that the approach adopted is a probabilistic one (i.e. based on predicting from historical data a rarer event equivalent to a return period of 1 in 10,000 years), rather a series of scenarios are postulated. The rationale for selection of the scenarios is not immediately clear, however it is suggested that the key influencing parameters are examined in terms of their influence on the overall result. Detailed guidance on propagation modelling is provided in Ref. 30.

193 The tsunami wave height is combined with the mean high tide level to give a total height of water that must be protected against at a site. For the Fukushima-1 site, the height determined was OP+5.7m. It is clear that the predicted values have fallen some way short of the actual values, however it is unclear why this is the case. There are many potential reasons, including, but not restricted to, failure to update the facility in line with new arrangements, scenario sampling, methodological inaccuracies and lack of suitable consideration of local bathymetric/topographic effects. The global movement of the land mass relative to the sea level also contributed to the depth of flooding.

194 It is clear that there have been historical tsunamis which have caused extensive damage around the Japanese coastline, including some in the Fukushima Prefecture. The level of data seen thus far has not enabled us to be categoric that tsunamis larger than the design value have been previously observed at, or close to the Fukushima site. The methodology in Ref. 30 does not require the design value to necessarily be larger than historical values provided certain conditions are met. However, it is clear that over the last 100 years Japan’s east coast has suffered several large tsunami (greater than 12m) associated with earthquakes some over 20 metres maximum height.

Key On-site Factors Relating to Electrical Systems

195 Generally most active safety provisions for nuclear power reactors require electrical power to operate, unless they are activated by loss of power. Therefore, to ensure safety at nuclear installations, electrical supplies have redundant and diverse provisions. This provides high confidence that electrical power supplies will be available in a range of fault conditions.

196 Details of the design of safety related electrical provisions serving the six nuclear power plants at the Fukushima-1 site is not readily available. However, from the information available it is clear that within a short time after the seismic event the essential electrical power supplies to safeguard safety related systems were rendered inoperable by the tsunami.

197 Information to date suggests that the site electrical power systems comprised:

- AC power systems with associated electrical power transformers, switchboards, switchgear and cables.
- Emergency power system for supplying those AC and DC loads required to fulfil essential safety functions. This system includes diesel generators, electrical batteries and associated charging systems.

198 The preferred source of electrical AC supply for normal and fault conditions is the Japanese grid supply system. Diesel driven electrical generators provide back-up electrical supplies to the emergency power systems in the event of loss of grid events and a diverse means of electrical power.

199 The initial seismic event disrupted electrical power supplies from the grid, resulted in a reactor trip and initiation of EDG operation. The emergency supplies systems appeared to have provided electrical power for essential safety functions until rendered inoperable by the tsunami. It is not known if inoperability of the diesel generators was because of flooding effects, mechanical damage to them or due to contamination/loss of diesel fuel.

200 The full extent of damage to the site electrical systems is not yet known. However, photographic evidence suggests that the site and off-site infrastructures were severely damaged.

201 AC electrical power was eventually provided from mobile diesel generators brought to site by helicopter because of the severe disruption to the road network from the effects of both the seismic event and tsunami. Electrical power from the mobile diesel generators has been provided to temporary pumps for reactor cooling. After many days a grid connection was established through installation of temporary cabling and used to supply the temporary pumps. Some equipment was moved to high ground in case there was another tsunami.

MAIN ASPECTS RELEVANT TO THE UK

Protection of UK Nuclear Power Plants from Natural Hazards

Overview

202 Within the UK, we are not subjected to particularly extreme natural hazards by comparison with many areas of Europe or the rest of the world. However, there have been some historical events which have caused widespread damage to areas of the country for example from flooding (2000) and high winds (1998). However, external hazards, including flooding, earthquake and wind are considered as part of the design basis for nuclear installations.

Regulatory Expectations

203 Within the HSE's Safety Assessment Principles (SAP), Ref. 2, there are very clear expectations laid out for the treatment of external hazards.

204 Within the Siting section it is stated that:

> *"103 Siting characteristics are relevant to various circumstances – new facilities or sites or modifications to them. The factors that should be considered in assessing sites cover three main aspects:*
>
> *a) the location and characteristics of the population around the site and the physical factors affecting the dispersion of released radioactivity that might have implications for the radiological risk to people;*
>
> *b) external hazards that might preclude the use of the site for its intended purpose;*
>
> *c) the suitability of the site for the engineering and infrastructure requirements of the facility.*

Siting	***External Hazards***	***ST.4***
Natural and man-made external hazards should be considered if they have the potential to adversely affect the siting decision.		

> *121 If the external hazards over which the duty-holder has no control are judged to be too great to be accommodated through the design of plant, the use of a site may be precluded for its proposed purpose."*

205 Within the broader context of external hazards it is stated that:

Engineering Principles: External and Internal Hazards	***Frequency of Exceedance***	***EHA.4***
The design basis event for an internal and external hazard should conservatively have a predicted frequency of exceedance in accordance with the fault analysis requirements (FA.5).		

Fault Analysis: Design Basis Analysis	*Initiating Faults*	*FA.5*
The safety case should list all initiating faults that are included within the design basis analysis of the facility.		

514 Initiating faults identified in Principle FA.2 should be considered for inclusion in this list, but the following need not be included:

a) faults in the facility that have an initiating frequency lower than about 1 x 10^{-5} pa;

b) failures of structures, systems or components for which appropriate specific arguments have been made;

c) natural hazards that conservatively have a predicted frequency of being exceeded of less than 1 in 10 000 years."

Engineering Principles: External and Internal Hazards	*"Cliff-edge" Effects*	*EHA.7*
A small change in DBA parameters should not lead to a disproportionate increase in radiological consequences.		

206 In summary, the design basis for external hazards is based on events with annual probability of exceedance of 1 x 10^{-4}, which has been conservatively defined. In addition, there should be a demonstration that there is no disproportionate increase in risk beyond this frequency – no "cliff-edge" effect.

207 Seismic and flood levels for UK nuclear licensed sites are summarised in Annex G.

Seismic Hazards in the UK

208 The UK is not generally associated with earthquakes, however, between twenty to thirty earthquakes are felt by people each year, and a few hundred smaller ones are recorded by sensitive instruments. This is because the UK is in an intra-plate zone, approx 1000 miles from the closest plate boundary and therefore suffers much smaller earthquakes. The largest recorded UK event is the 1931 Dogger Bank event of magnitude M_L 6.1. A magnitude 4 earthquake happens in Britain roughly every two years with a magnitude 5 roughly every 10-20 years. Research suggests that the largest credible earthquake in the UK is around magnitude 6.5.

209 The closest area to the UK that could give rise to an earthquake of comparable magnitude to the Japan event is in the Atlantic Ocean around the Azores. This is sufficiently remote from the UK that the ground shaking from any such earthquake would be much lower than the smaller earthquakes against which UK plant is shown to be robust.

210 The methodologies adopted for the development of the seismic hazard for nuclear sites in the UK are probabilistic in nature and are broadly equivalent to the approach adopted in the United States. The typical values of peak ground acceleration at UK sites for a 1 in 10,000 year event range from 0.15g to 0.26g, considerably lower than those experienced at Fukushima.

211 At this stage, the information emerging from the Tohoku event and its subsequent analysis is limited. The nature of the science of earthquake engineering is such that there will be lessons to be learnt over the propagation of ground motions from large events. These are considered unlikely to

be of immediate relevance to the UK hazard derivation; however, it will be prudent to examine this information as it emerges.

212 Although seismic events were not considered in the design basis of early nuclear plants in the UK, those designed after the early 1980's specifically include seismic loading as part of their design. For those built before this time, considerable effort has been expended to qualify the structures, plant and equipment against the requirements in the SAPs. This has included significant retrofitting of structures systems and components important to safety to ensure that safe shutdown, hold down and post-trip cooling functions can be achieved. As part of the periodic safety review process, the safety justification against natural hazards is re-evaluated on a ten yearly basis. Now all operating nuclear power plants in the UK have been shown to be sufficiently compliant with the expectations of our Safety Assessment Principles (SAP) (Ref. 2).

Tsunami Hazards in the UK

213 Historically, the UK has felt the effects of tsunamis. The main events of note are a small wave observed in some areas of the south of England following the Lisbon earthquake of 1755 and historical/geological data supporting large tsunamis affecting the far north of Scotland and Shetland following large-scale submarine landslides off Norway. Recently, public attention has been drawn to the disastrous flooding in areas bordering the Bristol Channel in January 1607, and it has been argued that this was the result of a tsunami. However, in this case, the combination of a high tide and a storm surge at the time provides a likely explanation for the flooding. UK earthquakes are too small to create tsunamis.

214 A detailed study was undertaken in 2005 (Ref. 31) to evaluate the risks to the UK. The conclusions were that the maximum tsunami height around the UK would be a 1-2m increase in sea level. Typically, it is argued that this increase is accommodated within the other contributors to sea level. These arguments are broadly accepted; however, they sometimes lack the level of rigour that might be expected.

215 Flood risks in the UK around nuclear licensed sites are discussed in Annex F.

Event Combinations

216 The range of external hazards considered in the design basis for nuclear installations is wide and diverse. In many cases, careful consideration needs to be given to concurrent hazards, for example, wind and snow and sequential hazards, in the case of Fukushima, tsunami following earthquake. In addition, there can be derivative hazards such as site/building flood following earthquake from failure of unqualified pipe work for example. The concurrent hazards are typically treated within the load schedule for structures, systems and components and are readily accommodated in the normal design process. In some cases it is difficult to assign a correlation factor and worst-case combinations are used. For sequential hazards it is common to assume that there is little or no damage from the first hazard which influences the capacity of structures plant and equipment to withstand the second hazard. This is the case for design basis and below scale events, however it may not be true for beyond design basis events.

Relevant Aspects of UK Reactor Technology

Introduction

217 The objective of this section of ONR's interim report to the UK Government is to provide a high-level overview of the technologies used in the UK nuclear power plants.

218 In addition, ONR and the Environment Agency are currently undertaking a Generic Design Assessment (GDA) of new nuclear reactor designs in advance of any site-specific proposals to build nuclear power stations in the future. The designs being reviewed are also addressed in this section of the report.

219 This section focuses on those features of the reactor technology that are relevant in relation to the challenges the Fukushima-1 reactor units were subject to. In particular, following the general introduction to the different technologies, five key aspects are discussed in some detail, i.e. control of reactivity (criticality), post-trip cooling, containment, severe accident management, and spent fuel storage.

The UK fleet

220 The UK operates the following reactors:

Table 5: UK Operating Reactors

Power Station	Reactor Type	Electrical Output per Unit (MW)	First Power Generation
Wylfa (twin units)	Magnox	475	1971
Oldbury (twin units)	Magnox	217	1967
Dungeness B (twin units)	AGR	520	1983
Hartlepool (twin units)	AGR	595	1983
Heysham 1 (twin units)	AGR	585	1983
Hunterston B (twin units)	AGR	430	1976
Hinkley B (twin units)	AGR	430	1976
Heysham 2 (twin units)	AGR	615	1988
Torness (twin units)	AGR	600	1988
Sizewell B	PWR	1188	1995

Generic Design Assessment (GDA)

221 In GDA we are currently assessing two new power station designs:

- The UK EPR^{TM}: Pressurised Water Reactor designed by EDF and AREVA.
- The AP1000^{TM}: Pressurised Water Reactor designed by Westinghouse.

The Advanced Gas-cooled Reactor (AGR) Technology

222 AGR technology differs significantly from that of Light Water Reactors and is unique to the UK. The AGR reactor core is assembled from high purity graphite bricks. These are keyed together in layers,

and are arranged in a polygonal structure with an overall diameter of approximately ten metres and a height of about eight metres. Circular channels in the bricks allow passage of fuel elements, coolant and control rods. The graphite also acts as a moderator.

223 The fuel in an AGR is slightly enriched uranium dioxide which is contained within stainless steel cans. The fuel is cooled by carbon dioxide which is chemically stable and not subject to any phase changes over the temperature range in which AGRs operate.

224 The reactor core is contained within a cylindrical pre-stressed concrete pressure vessel with top and bottom caps. On the inside of the concrete there is a gas tight steel liner. Normal operating pressures are 30bar to 40bar.

225 In an AGR the carbon dioxide heated in the reactor core moves through the primary side of the boilers and is then pumped back into the core with the gas circulators. The boilers are heat exchangers fed by water through their tubes (secondary side) where steam is produced which is directed to the turbine generator to produce electricity.

226 Compared with LWRs, the AGR energy density is low. In addition the thermal capacity of the reactor core is very high, due to the large mass of the graphite moderator. This means that if all post-trip cooling was lost following a reactor trip, the temperature increases would be slow allowing ample time for operator intervention.

The Magnox Technology (Wylfa and Oldbury)

227 Magnox reactors are the first generation of UK gas-cooled reactor. Only four, two at Oldbury and two at Wylfa remain operational. They are similar to AGRs in that they are cooled by carbon dioxide and graphite moderated. However, the fuel is natural uranium (i.e. not enriched) clad in a Magnox (magnesium non-oxidising) alloy. The operating cycle for a Magnox reactor is similar to that of the AGRs as described above.

228 Oldbury and Wylfa have pre-stressed concrete pressure vessels but operate at lower pressure and temperature than an AGR.

229 Magnox reactors, like AGRs, have a low power density and high thermal inertia. This means that if all post-trip cooling was lost following a reactor trip, the temperature increases would be slow allowing ample time for operator intervention.

The Pressurised Water Reactor (PWR) technology

230 Nearly 60 percent of the world's commercial reactors are PWRs. Sizewell B PWR is a development of a Westinghouse PWR design known as the Standardised Nuclear Unit Power Plant System (SNUPPS). The UK EPR^{TM} and the AP1000^{TM} are evolutionary PWR designs which incorporate advanced features in various aspects of the technology as discussed in the following sub-sections.

231 The PWR core consists mainly of fuel assemblies and control rods and is contained in a low alloy steel pressure vessel. Sizewell B's pressure vessel has an inside diameter of approximately 4.4 metres, a thickness of 0.21 metres and an overall height of 13.6 metres.

232 The PWR fuel is cooled by water which also acts as the moderator. The reactor operates at a pressure of 155bar.

233 As for AGRs, PWRs have separate reactor coolant system and secondary cooling system. The reactor coolant system is inside the containment. Sizewell B and the UK EPR^{TM} have four cooling

loops connected to the reactor each containing a reactor coolant pump and a steam generator which provides steam to the turbine-generators. The AP1000^{TM} has two cooling loops each containing two reactor coolant pumps and a steam generator.

234 The fuel in a PWR is slightly enriched uranium dioxide which is contained within zircaloy cladding.

Reactivity Control

235 The three Fukushima-1 reactor units that were operating at power at the time of the Tohoku earthquake shutdown automatically, i.e. the nuclear reactions were stopped successfully in the three reactors. The Fukushima-1 reactor unit reactivity control systems are described elsewhere in this report; the following subsections discuss the reactivity control systems in the reactors in the UK.

Advanced Gas-cooled Reactors

236 Typically there are three ways to control the reactivity in AGRs (with some variations among the different operating power stations), i.e. control rods, nitrogen injection system and the often called tertiary shutdown system:

- The primary means of shutting down the nuclear reaction for all the AGRs is the fall under gravity of control rods into the reactor core. There is a high level of redundancy in the control rod primary shutdown system. The nuclear reaction would be stopped by insertion of a small number of control rods, provided they were fairly uniformly distributed radially about the core.
- All AGRs have a diverse shutdown system some based on the rapid injection of nitrogen into the reactor core others on an adaptation to the main control rods. The primary function of the diverse shutdown systems is to provide rapid shutdown in the event of an accident that distorts the geometry of the core. Nitrogen absorbs neutrons and hence stops the chain reaction. Nitrogen injection would only be initiated if too few control rods had inserted following a trip. This injection is either by automatic means, or is manually initiated from the Reactor Control Desk. Those AGRs that do not have a nitrogen injection system are provided with articulated control rods. All AGRs have nitrogen injection but those with articulated rods have slower acting systems for longer term reactivity control.
- The tertiary shutdown is provided to maintain the reactor in its shutdown state in the longer term if an insufficient number of control rods have dropped into the core and it is not possible to maintain a sufficient pressure of nitrogen. The principle of a hold-down system is that neutron-absorbing material is injected into the reactor circuit. Such a measure would only be adopted as a last resort and is achieved by injection of boron beads or water.

Magnox Reactors

237 Following a reactor trip the nuclear reaction within a Magnox reactor would be shutdown by the fall under gravity of control rods into the reactor core. There is a high level of redundancy in the control rod shutdown system. The reactor would be shut down by insertion of a small number of control rods, provided they were fairly uniformly distributed radially about the core.

238 The primary shutdown system (control rods) has been provided with limited diversity by the installation of the Articulated Control Rods (ACR). These reactors also have a tertiary shutdown

system based on the injection of Boron dust but this action is irrevocable resulting in a permanent shutdown of the reactor.

Sizewell B

239 Core reactivity control during normal operation and shutdown in the event of a reactor trip is provided by the Rod Cluster Control Assemblies (RCCA). In a reactor trip the RCCA fall under gravity into the core which shuts the primary nuclear reaction down.

240 In addition to the RCCA, the emergency boration system provides a diverse means of shutting down the reactor.

241 In case both of the above systems failed, Sizewell B has ways to deal with such scenarios based upon the inherent characteristics of a PWR that would avoid reactor core damage.

Generic Design Assessment (UK EPR™ and AP1000™)

242 Consistent with the currently operated reactors in the UK, the UK EPR™ and AP1000™ have control rods which fall into the core under gravity. Like Sizewell B, if the control rods fail to insert both reactor designs take advantage of the inherent characteristics of the PWRs and have additional systems to add boron to the primary reactor coolant system to stop the nuclear reaction.

Post-trip Cooling

243 The Fukushima-1 reactor units had diverse means to cool the reactors following a reactor trip. From the moment in which all sources of AC power supply were lost because of the earthquake and the tsunami, the situation became a Station Blackout (SBO). The Fukushima reactor units had means to cool the reactors for a limited time using systems that only required DC power provided by batteries. These systems operated for some time in Reactor Units 1 to 3 as discussed elsewhere in this report. The following subsections discuss the post-trip cooling systems in the reactors in the UK.

Advanced Gas-cooled Reactors

244 The system for removing decay heat is known as the Post Trip Cooling System. Providing the pressure vessel is intact, the fuel is cooled by the gas circulators pumping the carbon dioxide coolant through the reactor core and boilers. The heat is removed from the boilers by the post-trip feed water systems which pump water through the boiler tubes.

245 If the gas circulators fail, the fuel can be cooled by natural circulation providing one of the boilers continues to be cooled by the feed water systems. All AGRs have at least two diverse post-trip feed water systems with redundancy and diversity in their electrical supplies.

246 If a breach has occurred in the pressure vessel then the fuel needs to be cooled by forced gas circulation and feed water supplied to the boilers.

247 The design basis safety cases are supported by the availability of 24 hours worth of stocks (e.g. diesel, carbon dioxide, feed water). This is on the basis that within that timescale it would be possible to obtain the required stocks to go beyond 24 hours. In reality, available stocks are normally provided for longer than 24 hrs as discussed elsewhere in this report.

Magnox Reactors

248 Magnox reactors have diverse and redundant systems for post-trip cooling. Providing the pressure vessel is intact the fuel is cooled by the gas circulators pumping the carbon dioxide coolant through the reactor core and boilers, with heat being removed from the boilers by the post-trip feed water systems.

249 Should the gas circulators fail then the fuel can be cooled by natural circulation providing the boilers continue to be fed. Tertiary feed and back-up feed are standalone systems with fuel and water for a minimum of 24 hours operation supplying both reactors.

250 If a breach has occurred in the pressure vessel the fuel needs to be cooled by forced gas circulation and feed water supplied to the boilers.

Sizewell B

251 Once the reactor is shutdown decay heat removal can be provided by a number of systems as described below.

252 Assuming the Reactor Coolant System (RCS) is intact, cooling can be provided by the following systems:

- Main Feed Water System (not backed by emergency diesels).
- Motor Driven Auxiliary Feed Water System consisting of two redundant trains, supplied by AC power backed by the emergency diesel generators.
- Turbine Driven Auxiliary Feed Water System consisting of two redundant trains. The system is supplied by steam from the steam generators, therefore it has self-sustaining motive power derived from core decay heat.

253 If the RCS is not intact, i.e. there is a coolant leak, make-up water and decay heat removal would be provided by the Emergency Core Cooling System. This consists of high head safety injection pumps, low head safety injection pumps and pressurised accumulators.

254 Heat sink for the post-trip cooling systems at Sizewell B is provided by the Essential Service Water System or the Reserve Ultimate Heat Sink (air cooled). These systems are backed by the essential diesel generators.

Generic Design Assessment (UK EPR™ and AP1000™)

255 The UK EPR™ has a motor driven Emergency Feed Water System with four redundant trains (including their own power supplies which are backed by emergency diesel generators). If the RCS is not intact, make-up water and cooling would be provided by the four train Emergency Core Cooling System. This consists of medium head safety injection pumps, low head safety injection pumps and pressurised passive accumulators.

256 As well as a two-pump motor driven steam generator feed water system, the AP1000™ has a passive decay heat removal system which does not rely on AC power. If the RCS is not intact, make-up water and cooling can be provided by a two train motor driven system or an independent and diverse passive cooling system consisting on core make-up tanks, accumulators and gravity injection from the large in-containment water storage tank.

Containment

257 As described earlier in this report, Fukushima-1 Reactor Units 1 to 5 have a Mark I containment with a drywell and a suppression pool with large volumes of water the function of which is to remove heat if large quantities of steam are released from the reactor. The BWR Mark I containment therefore provides a barrier against the release of radioactivity to the atmosphere and a short-term heat sink. Containment arrangements in UK reactors are discussed below.

Advanced Gas-cooled Reactors

258 AGRs do not have a containment building around the pressure vessel. This is on the basis of the longer timescales available in the event of loss of post-trip cooling and in recognition that the pressure vessel is a massive reinforced concrete structure. The AGR's concrete pressure vessel together with the large mass of graphite in the core provide hours of heat sink in case of total loss of cooling.

Magnox Reactors

259 The operational Magnox Reactors do not have a containment building around the pressure vessel, but, like the AGRs are provided with a concrete pressure vessel. As with the AGRs, the high thermal inertia means that there are long timescales available in the event of loss of post-trip cooling.

Sizewell B

260 The Sizewell B reactor is housed within a containment building which limits the release of radioactivity should a fault occur. This is a large structure made of pre-stressed concrete able to withstand substantial overpressure. In the containment heat is removed and pressure reduced by fan coolers and reactor building spray systems.

Generic Design Assessment (UK EPR^{TM} and AP1000^{TM})

261 Both UK EPR^{TM} and AP1000^{TM} have containment buildings fulfilling a similar function to that at Sizewell B. The UK EPR^{TM} containment is a two-walled concrete structure while the AP1000^{TM} has a steel vessel housed in a concrete building.

262 The UK EPR^{TM} containment can be cooled by an internal spray system and active cooling of the in-containment water storage tank. The AP1000^{TM} containment is cooled by pouring water from a large tank located on the top of the building onto the steel vessel.

Severe Accident Management

263 Once all the cooling capabilities were lost at Fukushima-1 Reactor Units 1 to 3, temperatures in the reactor cores would have increased rapidly and eventually core degradation started. From the onset of core damage, the three operating units at Fukushima-1 were in a situation of severe accident; this was accompanied by (visible) severe accident phenomena such as hydrogen explosions. Several actions were undertaken however by the operators at the Fukushima-1 site to arrest the progression of the accidents, e.g.:

- Venting of the primary containment in the three reactor units.

- Sea-water injection into the reactor vessels using temporary power sources and available injection lines started.
- Nitrogen injection into the Reactor Unit 1 primary containment.

264 All the reactors in the UK have in place arrangements to deal with situations of severe accident. These are discussed below.

Advanced Gas-cooled Reactors

265 Beyond design basis events such as total loss of power and loss of post-trip feed water are considered through the System Based Emergency Response Guidelines (SBERG) and the Severe Accident Guidelines (SAG). These make claims on the same systems as claimed for the design basis faults, supplemented by more novel arrangements (including the ability to mobilise specialist equipment, including back-up generation) supported by emergency plans.

Magnox Reactors

266 The situation for the Magnox reactors is very similar to the AGRs, i.e. they have Severe Accident Management Guidelines (SAMG).

267 As part of emergency arrangements, multiple connection points are provided on the feed systems to allow fire engines or other back-up equipment to pump water into the boilers.

Sizewell B

268 Sizewell B has in place SMAGs (embedded into its Station Operating Instructions (SOI)) and the means to deal with accidental situations, e.g. once all core capability has been lost. Examples are as follows (from Ref. 32 - *Level 2 PSA Methodology and Severe Accident Management*, OECD/GD(97)198):

- In order to avoid failure of the reactor vessel at high pressure in a severe accident, which may challenge the containment, the reactor coolant system can be depressurised using the pressuriser Pilot Operated Safety Relief Valves (POSRV), the pressuriser spray or by opening the upper head vent. This has been adopted as an accident management measure in the SOI.
- Hydrogen control is achieved by mixing the hydrogen that is produced in the containment atmosphere using the hydrogen mixing fans. Operation of the containment spray and the fan coolers also provides a mixing effect. In the longer term, the hydrogen recombiners can be used although their capacity is only sufficient for post-LOCA hydrogen generation. If all hydrogen recombining capacity is lost, the SOI allow the use of the hydrogen venting system in the last resort if the activity levels within the containment are sufficiently low.
- Water to cool a molten core outside the reactor pressure vessel and thus avoid basemat attack by molten core material (eliminating both melt-through and hydrogen production as a result of the core melt-concrete interaction) can be added to the reactor cavity using the containment fire suppression system which is separate from the normal safety systems and has its own diesel driven pumps and its own spray lines and nozzles inside the containment. This has been adopted as an accident management measure in the SOI.

Generic Design Assessment (UK EPR^{TM} and AP1000^{TM})

269 Both reactor designs have engineered features to manage the severe accident scenario. The AP1000^{TM} design floods the outside of the reactor to retain the molten core inside the vessel. The UK EPR^{TM} strategy is to cool any molten debris that escapes the vessel in a coolable concrete void (often called the core-catcher).

270 Both UK EPR^{TM} and AP1000^{TM} have methods for reducing the risk of hydrogen explosions. The AP1000^{TM} relies on hydrogen igniters to burn the hydrogen before the atmosphere in the containment becomes explosive. The UK EPR^{TM} relies on passive catalytic converters that remove any generated hydrogen from the atmosphere inside the containment.

271 Any future operators of either design will need to have in place adequate Severe Accident Management Guides (SAMG).

UK Reactor Site Spent Fuel Storage

272 Keeping the spent fuel ponds filled with water and adequately cooled has been a challenge at Fukushima following the earthquake and tsunami. As has been discussed earlier, the water inventory in the ponds needs to be maintained to protect the fuel from failing, to provide shielding, to prevent hydrogen formation and to avoid fuel fires.

273 None of the operating UK reactors have identical fuel or spent fuel facilities to those at Fukushima. Magnox fuel assemblies are clad in a magnesium alloy whilst the AGR fuel is clad in stainless steel therefore the chemical reactions of the cladding at raised temperatures and when exposed to steam/air are different from those experienced by zirconium alloys. However, the strategy of storing fuel underwater in cooled ponds is one which is utilised at almost all UK operating reactor sites during some of the fuel route cycle after removal from the reactors.

274 It should be noted that in the UK both AGRs and Magnox reactors use batch refuelling, so whole reactor core fuel inventories are not offloaded into the fuel ponds.

275 A summary of the spent fuel storage capabilities in the UK is provided below.

Advanced Gas-cooled Reactors

276 There are a number of design differences between the stations, but the overall fuel storage philosophy is the same. The fuel is discharged from reactor into a refuelling machine which is used to move the fuel to a dry buffer store pressurised with carbon dioxide. The fuel remains in the buffer stores for around 60 days to allow the decay heat to reduce. The spent fuel is then moved to a dismantling facility and then transferred to a water filled storage pond were it continues its storage period. The fuel in the storage pond is held in skips that can accommodate up to 15 fuel elements each. After at least 100 days storage the spent fuel is loaded into a transport flask and moved to Sellafield where it is either reprocessed or continues its storage.

Magnox reactors

277 At Oldbury spent fuel is discharged from the reactors into the refuelling machine which transfers the fuel to a discharge tube connected to the station pond. The spent fuel is stored in skips under water in the pond. The fuel remains in the storage pond for at least 90 days prior to loading into a flask for transport to Sellafield where the fuel is reprocessed.

278 At Wylfa spent fuel is discharged from the reactor into the refuelling machine which transfers the fuel to a dry storage facility. The fuel remains in storage in one of three dry stores which are pressurised with carbon dioxide. Once the spent fuel has cooled sufficiently it can be moved to two other on-site facilities that store the fuel in dry air. The fuel remains in the stores for at least 90 days prior to loading into a flask for transport to Sellafield where the fuel is reprocessed.

Sizewell B

279 Spent fuel is removed from the reactor under water during a station refuelling outage. The fuel is transferred via a water-filled canal to the station pond. The station pond can accommodate up to 1500 fuel assemblies and much of this in high-density stage racks. All of the Sizewell B fuel is stored in the fuel pond, although the station intends to develop a dry storage capability in a few years time.

Generic Design Assessment (UK EPR™ and AP1000™)

280 UK EPR™ and AP1000™ have similar strategies to that currently in place at Sizewell B. Fuel is transferred via an underwater canal, from the reactor to a fuel storage pond located outside the reactor containment in a contiguous building which is part of the nuclear island. Westinghouse and EDF and AREVA are developing plans to move spent fuel, after approximately 15 years of pond cooling, to additional on-site storage facilities for longer term storage.

Human and Organisational Factors

Severe Accident Management Strategy in the UK

281 In the UK, post fault operator actions on power reactors are typically governed by a suite of documentation to aid operator diagnosis and mitigation of the event. Severe Accident Management (SAM) involves the application of Symptom Based Emergency Response Guidelines (SBERG) and ultimately Severe Accident Guidelines (SAG). SAGs were developed post-Chernobyl in the mid 1990s (and received a minor revision in 2009), to provide operators with options and actions to consider in the event of a severe accident. They offer less prescription, are typically non-mandatory and aim to support a more innovative or lateral thought process. This reflects the fact that it is not (currently) considered practicable to anticipate the detailed plant conditions that would exist in such low frequency events.

282 Typically, during the transition between SBERGs and SAGs, as the event degrades into a severe accident, strategy and decision making authority transfers from the station/control room operators to the off-site Technical Support Centre, or other “higher level” decision making authority, and it is at this stage that the SAGs are applied. This reflects the recognition that decision making in a severe accident situation is highly complex in view of the uncertainties involved, and that mitigation actions may have consequences that go beyond the information available within the control room or even the plant. In a severe accident situation the operator’s role typically becomes one of action implementation.

283 Power reactor licensee training in the SAGs and SAM strategy is principally aimed at off-site technical support roles, rather than station personnel. Severe accidents are not routinely exercised in the UK. Typically, emergency exercises focus on design basis events (although they are extended

to test off-site response to release scenarios) There have been instances where exercise scenarios have degraded into severe accident territory; facilitating training in the application of SAGs.

284 Our enforcement principles are based on the concept of being proportionate to the risk, and this typically results in a focus of regulatory assessment on design basis safety cases and Level 1 PSA[d]. However, the industry are expected to have undertaken a range of assessment relating to severe accident situations, including their treatment in periodic safety reviews, qualitative reviews of SAG usability, and influencing the piloting of Level 2 PSA[d] for example.

Fukushima-1 Operator Actions

285 We do not currently have any detailed factual information relating to the severe accident management strategy employed at Fukushima-1; including the establishment of off-site technical support; the role of operators; the transfer to and declaration of a severe accident and the resultant employment of Severe Accident Management Guidelines (SAMG) in lieu of Emergency Operational Procedures (EOP); the decision making processes and command and control philosophy and structure in operation.

286 At this stage information regarding actual plant data throughout the accident progression is very limited. In our final report we will work with other agencies with a view to deriving a more detailed understanding of the operator actions and severe accident management strategy employed at Fukushima-1.

287 What is known are the high-level specific actions taken by operators and this information is provided elsewhere in this report. Essentially this included:

- Venting of reactor containment vessels.
- Injection of sea-water into the reactor pressure vessel.
- Injection of nitrogen into containment vessels.
- Provision of water to the cooling ponds, via non-conventional means.

288 We have considered equivalent plant SAMGs from a replica plant design (Quad Cities Generating Station Illinois, USA) and our initial understanding has been advanced. We are aware that there is some question regarding the timing of actions; although we do not yet have sufficient information to form a judgement on the lessons to be learnt from decision making process or the impact of key factors such as the availability of equipment; command and control issues, Critical Safety Function (CSF) prioritisation etc.

Implications for UK Power Reactor Facilities, Including New Nuclear Build

289 Our initial focus with regard to the human and organisational factors implications of the Fukushima accident is placed on severe accident management in general, rather than the response to the specific hazard affecting the Fukushima-1 reactor units.

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[d] Level 1 PSA identifies the sequences of events that can lead to core damage and estimates the core damage frequency. Level 2 PSA identifies the ways in which radioactive releases from the plant can occur and estimates their magnitude and frequency.

Availability of Personnel for Severe Accident Management

290 This appears to be a key issue and directly relevant to UK severe accident management. Typically UK safety cases make assumptions about the availability of personnel in defined off-site locations, within a specific timescale. We expect that the industry will undertake further work on the technical basis and derivation of off-site support locations and the appropriateness of the associated timescales, in light of predicted local damage zones resulting from extreme external hazards.

291 The availability of off-site technical support provisions also has consequential effects on the on-site severe accident management and response; as typically operators at the site become action implementers, and strategy and decision-making transfers off-site. Therefore if the time windows for off-site support availability are challenged, the industry should consider any resultant change in the role of on-site personnel and their requirements for support.

292 The number of on-site personnel and the availability of off-site support may affect decisions on the selection and prioritisation of actions to respond to the event. There are questions arising from this such as - are there sufficient numbers of people available to manage the range of actions that may be required concurrently, or over a timeframe according to what the accident management strategy is advocating? Moreover, UK safety cases assume the availability of on–site personnel for accident response by virtue of the fact that safety classified buildings and structures are designed and qualified against external hazards, (and certain concurrent external hazards). However, we do not consider that the effect of the external hazard on the availability and number of on-site personnel is typically considered by such analysis, and we expect the industry to undertake further work on this as part of our final report.

293 Safety cases also assume a willingness on the part of on-site personnel to respond to emergency events; whereas behavioural science literature and accident history indicate that this may not always be the case (for example operators left at Bhopal). We recognise the apparent willingness of operators to mitigate events at Fukushima, but we consider a review of the literature in this area to inform UK safety cases would make a useful contribution in building a more complete picture of the likely behavioural response. We further recognise the general and significant cultural and organisational differences between Japan and the UK; and the impact of this on the behavioural response and severe accident management strategy should be considered.

Command and Control

294 The current UK national emergency response arrangements and the Gold Command Structure are described in Annex D of this report.

295 From an organisational factors perspective we consider that the events at Fukushima potentially provides information about the command and control protocols relating to societal events. Further thought is required to maximise the provision of knowledge, technical advice and physical support to the event mitigation effort.

296 The deployment of armed forces and other agency support (including academics, and potentially personnel not trained in the nuclear hazard) in the accident management response over long periods requires further consideration. The factors we expect industry to consider include their availability, knowledge management, hazard awareness, role/position, responsibility and authority within the command and control structure.

297 We also consider that industry should review the human factor requirements for impact of external events on multi-unit sites. A common cause event leading to beyond design basis accidents on multiple units will place heightened demands on the workforce and command and control organisation, which is typically focused on a unit by unit response.

Technical Support – Severe Accident Management Guidelines and Training

298 In the final report we will consider the industry's review of the suitability of Severe Accident Management Guidelines (SAMG) for supporting operator actions, informed by information on the success or otherwise of the postulated operator actions at the Fukushima-1 site. In particular such a review should consider the critical safety functions prioritisation, and wider plant requirements, and the level of detail and prescription currently offered. It should also consider whether and how the SAMGs support any dynamic re-prioritisation of goals, criteria and objectives based on emerging plant predictions and prognoses. We recognise that this may result in a requirement for research to improve understanding of AGR and PWR accident phenomenology, and we will ask the industry to consider the potential safety benefit of this as part of our investigations in this area. In addition we will expect the industry to review whether any customisation of SAGs is required to account for station differences and their risks to external hazards.

299 Furthermore we consider the industry should review any consequential impact on operator (and other personnel) training requirements. We recognise the limitation of current simulator models to support the formal training of severe accident management, and will consider the reasonably practicability and safety benefit of extending routine training in severe accident response.

Availability of Control and Instrumentation, Including Communications and Equipment and Power Supplies

300 Equipment and power supply availability is considered elsewhere in this report; the pertinent human factors issues in this regard are the deployment, availability and usability of equipment and the design of (simple) engineered measures that can be employed in a severe accident.

301 Current UK safety cases do not generally consider the total loss of Control and Instrumentation (C&I) as experienced by the Fukushima-1 reactor units due to the fact that design standards require equipment to be qualified against postulated hazards. In addition UK power reactor facilities have Alternative Indication Centres (AIC) and Emergency Control Centres (ECC) on-site that contain key parameter data, and these are safety-qualified buildings. From a human factors perspective and based on a greater understanding of the events at Fukushima, further consideration should be given to data availability (and the scope of equipment qualification) in a severe accident situation; the situation and progression through time of such events; and the location of any data relay in view of likely zones of damage. For example consideration may be given to the provision of off-site data banks that record key parameters such that reference data is available at the time when the hazard occurs.

302 For new plants the industry should explicitly highlight the design features that eliminate (some) severe accident phenomena and the dedicated equipment provided for managing beyond design basis accidents.

303 There is also a need to consider the availability of, and protocols for communication facilities in a severe accident situation.

Doses to Intervention Personnel

304 With regard to the Japanese response to the nuclear emergency at the Fukushima-1 site, it has been necessary for the operator's staff and emergency services, in seeking to restore cooling, to incur radiation exposures considerably in excess of the 100mSv emergency dose limit that is applied in Japan. For this work doses up to 250mSv have been authorised, and 30 people closely involved with the emergency have received doses between 100-250mSv.

305 Similar arrangements apply in the UK. In the event of a radiation emergency, it is recognised that higher doses may need to be incurred provided that the likely benefits in terms of life saving clearly outweigh the risks to those carrying out the intervention. If interventions require emergency workers to receive a dose greater than the limits specified in the Ionising Radiation Regulations 1999, then the Radiation (Emergency Preparedness and Public Information) Regulations 2001 (REPPIR) disapply the normal dose for the purposes of intervention. REPPIR require operators to notify HSE of the dose levels they have determined to be appropriate for intervention workers in the event of a radiation emergency.

Public Protection Countermeasure Zone

306 Initially Japan implemented a 3km radius evacuation zone and a 10km radius shelter zone. This was quickly extended to 10km radius evacuation zone and 20km radius shelter zone, and then later to a 20km radius evacuation zone and 30km radius shelter zone. This is similar to the UK arrangements where immediate countermeasures are implemented in accordance with the off-site emergency plan, but can be extended in terms of distance or increase in countermeasures, e.g. from shelter to evacuation, as the event unfolds.

Distribution of Potassium Iodate Tablets

307 The Japanese do not pre-distribute potassium iodate tablets to those within the predetermined emergency planning zone. In response to the Fukushima emergency, potassium iodate tablets were distributed to evacuation centres within three days. Tablets were not distributed to evacuees until nine days into the accident. The UK provided potassium iodate tablets to the British Embassy in Japan.

308 Potassium iodate tablets are only needed around sites where there are nuclear reactors, and in the UK the tablets are pre-distributed to residents within the Detailed Emergency Planning Zone (DEPZ), including schools and hospitals etc., as they provide greater protection from radioactive iodine if they are taken just before an exposure occurs.

Monitoring, Decontamination and Medical Assistance of Evacuees and Casualties

309 Monitoring and decontamination units were employed at evacuation centres to identify those who may have been contaminated and to provide reassurance monitoring to those who were not. It is believed that contamination was identified on a few evacuees who were successfully decontaminated at the evacuation centre. During the emergency, there were a few workers who received significant skin doses to their feet or lower legs (believed to be 2-3Sv) and were taken to hospital for medical treatment and later discharged.

310 UK arrangements include the provision of monitoring and decontamination units, and local hospitals are identified that have the facilities and trained, competent staff to receive irradiated or contaminated casualties.

Radiological Monitoring of the Environment

311 Widespread environmental monitoring of the environment was implemented across Japan, including measurements of air concentrations, ground deposition, water and foodstuffs within a few days of the earthquake. Radiation monitoring during and after a nuclear emergency plays an important role in providing an input to decision making and in the provision of information to the public and to official bodies. Monitoring undertaken might relate to the immediate impact of the accident on people and the potential future impact resulting from environmental contamination. Within the UK, responsibilities for radiation monitoring in the event of a nuclear emergency lie with a number of organisations. The licensee carries out monitoring of the area immediately surrounding the facility, out to a pre-determined radius. HPA's Radiological Protection Division (RPD) co-ordinates activities beyond this. During the Fukushima accident, international assistance was requested due to the widespread dispersal of the contamination.

Taking Agricultural Countermeasures, Countermeasures against Ingestion and Longer Term Protective Actions

312 In Japan, milk, leafy green vegetables and drinking water were found to exceed regulation values in some localised areas and restrictions were implemented. Discharges to sea of contaminated water resulted in fishing bans within 30km of the Fukushima-1 site being implemented along with a change to the regulation value of iodine-131 in fishery products being implemented.

313 Where radioactivity is released into the environment, the criteria for intervention in food safety in the UK (at least in the early phase of the emergency) will be the Council Food Intervention Levels (CFIL) laid down by the European Union. These are based on the contaminated food being consumed at the indicated level of contamination for a whole year to avert a dose of 1mSv.

314 If it is assessed that levels of radioactivity in any potential food products may exceed the CFILs as a result of an accident, the Food Standards Agency (FSA) will describe the area in which the relevant CFILs might be exceeded, name the food products affected and advises on the actions to be avoided (e.g. eating, collecting, harvesting or transporting).

315 FSA are responsible for ensuring the public is protected from contaminated food, including taking action to ensure food contaminated to unacceptable levels does not enter the food chain, implementing, where necessary, restriction orders under the Food and Environment Protection Act 1985.

316 Defra has responsibility in a nuclear emergency to protect animal welfare and to minimise the impact of the emergency on food production, farming and fishing industries.

317 The disposal of any radioactive waste arising from decontamination and clean-up following a nuclear emergency shall be handled on the basis of advice from the Environment Agency or SEPA in Scotland. The Environment Agency / SEPA will advise on the most appropriate means of dealing with the waste and, where necessary, arranging for its disposal. FSA will also help to advise on the disposal of contaminated foodstuffs.

Robustness of the UK Grid

318 The UK Grid system in most situations will provide external power to support the electrical systems of nuclear power plants when their main generators are not operating. The grid is the primary source of back up power to the nuclear power plant and provides a reliable source of external power. The UK Grid is a key national infrastructure and has been designed to withstand a wide range of internal faults and external hazards such as extreme weather events. However, despite the excellent track record of the UK Grid all nuclear power plant licensees are required to provide considerable defence against both short and longer term loss of grid connection.

319 Faults do occur on the grid network as documented on the National Grid Website and these do result in loss of connections at nuclear power plants. Many grid faults do not result in loss of supply at the grid connection point due to multiple transmission lines being provided to the nuclear power plant grid substations and the availability of reserve capacity from other generators. In normal operating conditions most faults which cause total loss of grid connection are cleared in less than three hours.

320 Although the grid provides a reliable source of power in normal conditions on-site sources of standby generation are provided to maintain essential services following loss of grid connection. These maintain power to essential services on the plant independently of the grid. In severe accident scenarios caused by external events such as severe weather the grid system could be subject to disruption by the same events as the nuclear power plant. Thus, it can be more likely that connections will be lost in these situations and service must be maintained from the on-site sources of power until the grid supply can be restored. Restoration times for grid supplies are also likely to be extended during severe accident scenarios so the on-site power sources must have the capability of maintaining essential services for an extended loss of grid supply. All of the UK's nuclear power plant have to provide back-up systems capable of sustaining safe operation not only for short duration loss of grid events but for loss of grid events that can last for more than a day.

An Initial Response from Magnox Limited and EDF Energy (Existing Fleet)

321 As part of the work to prepare an interim report ONR had submissions from those licensees who operate nuclear power stations in the UK.

Magnox Limited

322 This response notes that Magnox Limited run two operating reactor sites, three sites undergoing defueling and five sites undergoing decommissioning. The following responses on spent fuel storage were noted:

- *"Wylfa and Oldbury have irradiated fuel stored on-site in dry stores (Wylfa) and ponds (Oldbury). These will also be considered as part of the company's safety case review (see below) especially as experience from Fukushima demonstrates the importance of controlling fuel temperatures. This will be important for both Wylfa and Oldbury due to the presence of short cooled fuel in their storage facilities."*
- *"For sites only undertaking defueling, i.e. Chapelcross, Dungeness and Sizewell, the reactor risk is lower since these sites have been shutdown for over four years and fuel cooling is now achieved passively. Therefore, for these three sites the concern would be events that prejudiced the fuel storage ponds such that there may be a loss of the radiological shielding provided by the water. Although less of an issue in terms of off-site release and dose to members of the public, recovery actions by the operator would be difficult and further operator guidance and/or facilities may be appropriate in response to such an event."*
- *"Recognising the role of the operator in responding to extreme events it would be prudent to review our* [Magnox Limited] *SBERGs (Symptom Based Emergency Response Guidelines) and SAGs (Severe Accident Guidelines) to determine if any improvements could be made. Training in and practicing of the deployment of these guidelines will also be considered."*

323 Information released so far regarding the Fukushima-1 accident has been considered by Magnox Limited and potential early lessons have been identified. These principally relate to a proposed review of relevant safety cases and their design bases, consideration of enhancing guidance to operators for extreme events and review of off-site equipment and support and how this may be deployed in the event of major national infrastructure damage. Magnox Limited will be pursuing these issues in advance of any further information and are establishing a project team specifically for this purpose.

EDF Energy (Existing Fleet)

324 EDF Energy's response provides a view on the seven AGR sites and the Sizewell B PWR. Its preliminary response was:

- *"The AGR fuel ponds and buffer stores are water-cooled. For the newer AGRs, there is redundancy and diversity in these systems; for the older AGRs arrangements are in place to provide defence in depth."*
- *"At Sizewell B fuel is stored in the fuel storage pond with a minimum of eight metres of water above the top of the active fuel. Water can be made up from numerous systems but if these are not available then provision is provided to provide make up water using a fire tender parked outside of the fuel building via an engineered penetration into the fuel building."*

- *"EDF Energy (existing nuclear power stations) has initiated a mandatory evaluation across the company on issues which have already emerged on the events at the Fukushima-1 site."*

325 Both Magnox Limited and EDF Energy Existing Nuclear have initiated a series of reviews in response to the events at the Fukushima-1 site. This includes a review of UK plant condition and severe accident guidance.

DISCUSSION

Introduction

326 Two months after the devastating events in Japan, there is much we still do not know about the nuclear accident at Fukushima-1 (Fukushima Dai-ichi). However, there is sufficient information to develop initial lessons for the UK. It is known that the reactors and associated plant largely survived the ground motions from the largest earthquake recorded in Japan. The operating reactors shutdown within seconds, and reactor cool down commenced using on-site emergency electrical power as the earthquake took out the off-site grid supply. About an hour later a large tsunami (reported to be some 14m above datum reference levels) hit the site and rendered the emergency diesel generators and essential electrical switchgear inoperative. Within a short time battery operated emergency cooling stopped and reactor temperatures, without means of control, started to rise unrestrictedly. Thereafter the operators had to seek other innovative and untried means to cool the reactors and associated spent fuel ponds.

327 In summary, the plant on the site sufficiently survived the ground motions of the earthquake observed at the site but not the associated tsunami. Although design provisions appear to have been made to protect against a 5.7m surge in sea level above datum, there is a history of larger tsunamis hitting this coast of Japan. It is reported that over the last 150 years Japan has experienced several tsunamis of height greater than six metres, and some over 20 metres. However, the equivalent wave heights for these events at the Fukushima site are not known. Such large earthquakes and their associated tsunamis are not credible for the UK.

328 In light of these and other facts considered earlier in this report, this section discusses potential lessons using the outcome of independent technical reviews undertaken nuclear inspectors from the Office for Nuclear Regulation (ONR), focusing on aspects relevant to the UK nuclear power industry. We have greatly benefited from the various submissions provided by others and, especially, from the work of the Technical Advisory Panel. Some more general matters are also addressed that come out of various comments or concerns arising from the circumstances of the accident. Conclusions are derived as are recommendations for further work to identify potential areas for improving safety.

329 In considering these findings, it is important to recognise that a sustained high standard of nuclear safety requires the application of the principle of continuous improvement. This principle is embedded in UK law, where there is a continuing legal requirement for nuclear designers and operators to reduce risks so far as is reasonably practicable. This is underpinned by the requirement for UK operators to undertake detailed, periodic reviews of safety and to seek further improvements[e]. Such periodic reviews, which have been a requirement of the UK's nuclear site licensing regime for many decades, are now a feature of the International Atomic Energy Agency (IAEA) Safety Standards.

330 This approach 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, and from new knowledge and experience, both nationally and internationally, must continue to be a fundamental feature of the safety culture of the UK nuclear industry.

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[e] An illustration of the impact of such regulatory requirements is that the periodic review for Dungeness B resulted in the operator spending around £100m on keeping it in line with developing standards.

Context

331 Before considering the initial lessons learnt and recommendations arising from our work so far, it is instructive to look at the effects of the Fukushima accident in the context of the wider devastation caused by the earthquake and tsunami on 11 March 2011. From the direct effects of the earthquake and tsunami over 14,000 people have been confirmed dead with over 11,000 missing. To date no person has died as a result of radiation exposure from the associated nuclear accident, although the assumption is any exposure to radiation incurs some risk. In time, with radiation exposure to a large enough population, some deaths may be attributed to it.

332 It is understood that around 30 workers at the Fukushima plant have been exposed to radiation exposures of between 100 and 250mSv. These doses, although significant, would not be expected to cause any immediate physical harm, although there may be a small percentage increase in their risk of eventually contracting a life threatening cancer[f]. Three workers are reported to have suffered acute radiation burns (non-stochastic effects) on their feet/legs from inadvertent exposure to heavily contaminated water in a turbine basement. After hospital treatment they were released after four days with reported no long-term likelihood of significant harm. It is also reported that two workers on site are confirmed as dead (from other than radiation exposure) and several injured. A further worker was reported on 14 May 2011 to have died from exhaustion.

333 To avert potential radiation exposure to the public, the Japanese authorities took the precautionary action of advising those within the first 3km, then 10km, and finally 20km of the plant to evacuate and those between 20km and 30km to stay indoors and get ready to evacuate. This advice remains in place after several weeks. Information on the likely exposure of the public is not yet clear, although evacuation and sheltering would have limited exposure.

334 While there appear so far to have been few radiological health consequences the societal and environmental impacts of the accident have been extensive and far reaching, with tens of thousands of people being evacuated from around the plant, foodstuffs being banned, some drinking water restrictions, and significant contamination of the sea. In addition there has been great public anxiety, both in Japan and internationally, about the possible health and other impacts of the radioactivity released. Finally, the economic impact of the failure of the plant is very significant.

335 The direct causes of the nuclear accident, a magnitude 9 earthquake and the associated massive tsunami, are far beyond the most extreme natural events that the UK would be expected to experience. The UK is, reassuringly, some 1000 miles from the edge of a tectonic plate – where earthquake activity and severity is greater. Additionally, UK nuclear power plants, both those operational and those planned, are of a significantly different design to the Boiling Water Reactors (BWR) reactors at the Fukushima-1 site. Furthermore, our approach to design basis events and analysis seems different. In particular, we require designers and operators to ensure that adequate protection is in place for natural events of a remote nature, based on an extrapolation from the historical record, and then we look to see that there are no “cliff-edge” increases in risks and that more could not be reasonably done to protect against very remote events.

336 Having reviewed what we know about the direct causes of the accident and considered the response of the UK operators, we are satisfied that there is no need for immediate action to

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[f] See Annex B comparative impacts of dose.

improve safety for operating nuclear power reactors, although longer term improvements may be identified from consideration of the recommendations.

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.

337 However, severe accidents can arise from other causes and learning from events such as that at the Fukushima-1 site is fundamental to testing the robustness of defence in depth provisions and enhancing them if needed. This is to ensure that the multiple independent barriers that are in place to prevent a major release of radioactivity are reinforced, even for very rare events. This accident emphasises the need to pay particular attention to “cliff-edge” effects especially those associated with common causes such as extreme weather. This is to ensure that by using the principles of redundancy, diversity and segregation a high standard of protection is provided.

338 Despite the differences between the situation at Fukushima and in this country, and in line with the fundamental principle to ensure and maintain nuclear safety, 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.

339 It is in this context that the following conclusions and recommendations are proposed.

Interim Report Findings - General

340 Although the main focus of this interim report is to identify potential lessons for nuclear power plants in the UK (other parts of the nuclear industry will be covered in the final report), there are aspects of a wider national and international application that have become apparent. These general aspects are considered first. In addition, there are some specific recommendations which are relevant to the whole of the UK nuclear sector. Thus we anticipate that the whole sector will consider them for relevance to their operations.

International Arrangements for Response

341 In the early days of the accident the focus for many nations was to understand the circumstances of the accident, what the radiological consequences were, and what these might mean for their citizens. There were difficulties in obtaining authoritative information needed by national experts and authorities in order to make independent predictions of the potential impact on their citizens in Japan or elsewhere. There was significant international co-operation especially between regulatory bodies and the IAEA that helped to fill in some of these information gaps.

342 However, the endeavours of national and international bodies would have been greatly assisted by earlier availability of authoritative information on such matters as: design of the plants affected, the inventory and history of the nuclear fuel in the reactor cores and storage ponds, its condition, etc. Discussions on this matter have been initiated within the international community. It is our view that these requirements should be addressed, e.g. by IAEA being given timely access to such information from the country in which a severe nuclear event occurs, and by IAEA acting as the authoritative distributor of that information.

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.

343 It is noted that other international initiatives and reviews have been set in train which may well lead to further recommendations for improvement in international or other arrangements. These initiatives may include expanded scopes for international peer review missions conducted by IAEA and the World Association of Nuclear Operators (WANO). For example, the reviews by WANO do not focus on design matters but on operational matters and in doing so have been particularly effective in enhancing the safe operation of nuclear facilities. The UK nuclear industry makes extensive use of such WANO review missions. An update on relevant changes to international arrangements will be covered in the final report.

National Emergency Response Arrangements

344 The Japanese authorities' implementation of off-site countermeasures appear to have been effective in protecting the population from significant harm from the radiological releases from the Fukushima-1 plant, despite the widespread devastation caused by the earthquake and tsunami. There may be lessons for the UK in the way these countermeasures were organised and implemented, not only in relation to emergency arrangements for a major nuclear incident in the UK but also for wider civil contingencies arrangements for dealing with severe disruption of infrastructure and threats to population from any cause. This should be the subject of a review initiated by Government, involving the Cabinet Office, and relevant departments, agencies as well as the regulatory bodies. It should take account of any social, cultural and organisational differences especially in light of tendencies to self evacuate.

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.

345 This was a particularly demanding nuclear accident in that the threat of significant radiological release continued for weeks before some degree of reliable control was established, and it was in the context of massive infrastructure disruption. Such circumstances have the potential to stretch resources at all levels, both in the country affected and in other countries seeking to provide advice to their citizens at home and abroad. In light of the extended Japanese emergency, it is recommended that the UK's nuclear emergency response arrangements are reviewed for nuclear incidents that might occur both in the UK and overseas. This should be co-ordinated through the Nuclear Emergency Planning Liaison Group (NEPLG) which is led by the Department of Energy and Climate Change (DECC).

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.

346 The review should particularly consider the capacity and capability for sustained widespread environmental monitoring, and the co-ordination of resources for radiation monitoring.

Response of the UK Nuclear Industry

347 The UK nuclear power industry has had a good safety record, especially over recent years. Under its present leadership it is developing a more open approach, in particular in seeking to learn lessons from the events at the Fukushima-1 site despite the differences between the technology employed in the UK to that involved in the Fukushima accident. We have been reassured by:

- The industry's 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 nuclear reactors.
- The industry's intention to complete further reviews.

348 This is in line with a continuous learning culture that puts safety at the top of a company agenda.

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.

Openness and Transparency

349 There was some comment internationally, especially in the early stages of the accident, about the lack of information provided by the Fukushima operating company, the Tokyo Electric Power Company (TEPCO). This no doubt added to reported speculation that TEPCO had been slow to release information on events in the past, even to government bodies. It is reassuring, however, that TEPCO is now providing significantly more up to date information on the Fukushima accident.

350 It is important at times of great concern, such as when a nuclear event occurs, that the public has access to up to date, comprehensive and reliable information. Public trust in the quality and provenance of such information is crucially dependent on a history of honesty, openness and transparency with regard to the activities of both the industry and the national regulators.

351 Although great strides have been made to increase openness and transparency in the UK, these have not always been commensurate with changes in society's attitude to experts, technology, etc and with expectations of access to information driven by advances in information technology.

352 As part of our development as a forward looking regulator, in recent years we have pushed forward our openness and transparency agenda. With our recent move to become the Office for Nuclear Regulation (ONR), and the greater freedoms that should bring, we intend to accelerate this programme and seek to match society's expectation. This will involve a significant organisational commitment and further resources, not only to provide more and timely information, but also to produce it in a form that recipients find useful. Additionally, it is our intention to consider creating a new regulatory advisory committee to which we will periodically report our work and seek its views. This will be done in an open and transparent way. The UK nuclear power industry has expressed its support of the openness and transparency agenda.

353 Some stakeholders have reservations about greater openness and access to information, based on concerns about the potential for misuse by the media or others and possible detrimental effect on our regulatory effectiveness. We acknowledge that there must be some limitations, especially with regard to matters of security, but we believe such reservations must not stand in the way of our drive for greater openness and transparency. The recent comments over information release by

TEPCO and distrust in its provenance provide a striking illustration of why ONR is addressing this issue with commitment and urgency.

354 Similarly, it is recommended that the UK nuclear industry consider how it can accelerate its move to a more transparent and open relationship with the public.

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.

Interim Report Findings - Relevant to the UK Nuclear Safety Regulatory Regime

Regulatory Status

355 People's concerns about nuclear and radiological hazards, and the potential societal and environmental impact of nuclear accidents, are reflected in the stringency and intrusiveness of the nuclear regulatory regimes worldwide. IAEA has developed international standards for such regimes, which are reflected in various international conventions and, for Europe, in a recent Nuclear Safety Directive. These standards are predicated upon national systems of nuclear licensing, and strong, independent regulators with stringent inspection and enforcement powers. The precise nature of these regimes and their constitution vary around the world. Some are highly prescriptive in nature, while others are goal-setting, depending on the particular legal, cultural, industrial and historical background of the country involved.

356 National nuclear regulatory regimes are subject to peer review both under the international conventions and by IAEA-led teams of senior regulators from around the world. The UK regulatory system has undergone two IAEA reviews in the last five years and, along with other nations, in April 2011 was subject to peer review under the provisions of International Convention on Nuclear Safety (CNS). Documentation relating to these reviews is publicly available. In the wake of the Japanese accident these international mechanisms are being examined to see whether there is a need for further strengthening, especially as there are more than 60 nations without any nuclear power experience wishing to develop such programmes.

357 We are aware of some comment about whether the Japanese nuclear regulatory regime ensures that the Japanese nuclear regulatory body has sufficient independence and powers. However, we do not consider that there is currently any evidence with regard to the accident at Fukushima to consider this matter. We understand that the Japanese government has had in mind some clarification of the role of its regulatory body, and fostering different relationships between industry and its regulator in response to the IAEA led International Regulatory Review (Ref. 4).

358 In the UK such concerns about nuclear regulatory independence and powers are not so apparent. In considering the accident in Japan and the potential lessons to be learned for the UK, we have not identified any significant weaknesses in the existing in the existing nuclear regulatory regime. Nevertheless, changes underway are designed to create a more integrated, focused, independent and accountable UK nuclear regulatory body. It will have greater institutional flexibility to sustain the expert resourcing we will require to meet the challenges of the future.

359 The Government announced earlier this year that it would take forward proposals, to create an Office for Nuclear Regulation (ONR) as a standalone statutory corporation outside the Health and Safety Executive (HSE). This would enable the nuclear regulatory body to employ its own staff and would enhance independence by placing the role, powers and duties of the Chief Inspector

(including granting nuclear site licences and attaching conditions) into statute for the first time rather than relying on delegated powers given administratively through HSE. The creation on 1 April 2011 of the Nuclear Directorate as an agency of HSE and its renaming as the Office for Nuclear Regulation is an interim step. This move should enhance confidence in the independence and robustness of the UK nuclear regulatory regime.

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.

Safety Assessment Approach

360 ONR uses its established Safety Assessment Principles (SAPs) as the basis for assessments of nuclear plant safety cases and to judge the safety of nuclear facilities in the UK. To date, our review of the circumstances of the Fukushima accident has not exposed any significant gaps in our SAPs. This is not surprising as the SAPs have relatively recently been reviewed against the latest international standards. Nevertheless, we consider that it is prudent to undertake a more detailed review of the SAPs as we obtain further information about the Fukushima accident and the reviews that nuclear licensees are undertaking, drawing as well on the outcome of IAEA, the Nuclear Energy Agency (NEA) of the OECD and European work.

361 A useful demonstration of the advantages of the UK regulatory approach is in seismic/tsunami design. Our SAPs require a rigorous approach relative to our history of seismic activity and associated flooding. We require the use of historical information to develop predictions of a more extreme event - a one in ten thousand year seismic event, and for the designer to demonstrate adequate protection against it. Additionally, we require the designer/operator to determine where there are any "cliff edge" effects and whether more protection can be reasonably put in place for even more remote events. It may be noted that a cause of the Fukushima accident appears to be the disproportionate increase in consequences following a tsunami with a height which exceeded the level considered in the design. However, in considering any responses to the recommendations made here and to the proposed European Council "stress tests" (www.wenra.org) may lead to additional guidance, particularly on "cliff-edge" effects.

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

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 light of the Fukushima accident, particularly for "cliff-edge" effects.

Emergency Response Arrangements and Exercises

362 There are lessons to be learnt for the regulatory regime from the accident and the response in the UK. The extensive and extended nature of the Fukushima accident indicates that there is a need to consider extending some emergency exercises in the UK to include severe accident scenarios. ONR's incident response centre at our headquarters in Bootle, Liverpool was staffed and

operational for over two weeks, including some overnight working. Similarly, the UK nuclear power industry set up its own crisis centre. Its use for such a long period has led to some areas where improvements may be made through exercising in real time such matters as: hand-over arrangements, sustainability of resourcing, the provision of technical advice in short timescales (tailored to the needs of different recipients), and the vital role of communications and the acquisition of reliable data. For effective response to any UK incident there may be benefits in the regulator having direct access to real time independent information of key parameters from the affected site, if practicable. This is the case in some other countries. Additionally, there would be advantages in having available for each site a suite of radiological release calculations, release categories and associated dose rate predictions.

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.

363 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. As we note above, however, the changes planned to place ONR on a statutory corporation basis, will provide an independent, robust regulatory body fit for the challenges ahead.

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.

Interim Report Findings - Relevant to the Nuclear Industry

Off-site Infrastructure Resilience

364 One of the particular aspects of the Fukushima event was the severe disruption of the electrical grid, communications and transport systems. This lasted for several days and while in itself was not sufficient to cause the accident it was a significant contributory factor. Other nuclear power stations were similarly affected by such disruption of the infrastructure, in particular the Fukushima-2 (Fukushima Dai-ni) nuclear power site located some 11 km away from the Fukushima-1 site, but while having problems these did not escalate into the problems experienced at Fukushima-1.

365 This raises the question as to what extent the nuclear safety of a site is reliant on the resilience of the local infrastructure in circumstances of extreme events affecting both the nuclear site itself and the surrounding area.

366 Severe accident management provisions for UK nuclear plants have been enhanced over the years with licensees introducing off-site storage of emergency equipment along with enhanced accident

management off on-site capabilities. However, these preparatory actions have generally been predicated on an event that would only affect the site itself. In Japan, however, although the Fukushima-1 reactor units' reactors and their safety systems withstood the ground motions caused by the earthquake, the off-site electrical grid system did not. This, together with the loss of on-site AC electrical equipment following the tsunami contributed to the inability to deal with the event.

367 Given the experience in Japan, we consider that the dependency of the UK's existing and planned nuclear plants on the resilience of off-site infrastructure should be re-examined. This examination should take into account: the extreme natural events that can reasonably be predicted, the timescales for recovery of such infrastructure, the logistics of getting essential supplies and equipment to site, and the ability of the site to survive in the interim with its own resources. This might highlight the need for enhancement of site's self-sufficiency for extended periods in terms of electrical power, coolants and supplies, including those to sustain human intervention.

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 the reliability of the grid under such extreme circumstances.

368 Further work is needed to understand the particular elements that determined the ability of the reactors at the Fukushima-2 site to remain safe while the Fukushima-1 site had great difficulties. This may reveal some particular elements that merit consideration for UK nuclear facilities.

Recommendation 9: Once further relevant information becomes available, the 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.

Siting of New Nuclear Power Stations

369 Questions have been raised as to whether there are any lessons for the existing siting policy and strategy for new reactors in the UK. Two main aspects in relation to the Japanese accident are:

1 The location of a site in areas subject to particular onerous natural hazards.

2 The ability to implicate precautionary counter measures such as evacuation.

These are considered below.

Impact of Natural Hazards

370 Seismically, the UK is in a relatively inactive area, unlike Japan, being well away from any tectonic plate boundaries. Nevertheless, as discussed earlier, we require that new nuclear facilities are designed against extreme external events including earthquakes of a severity greater than those in historical records for the UK. We have already noted that the response of the Japanese plants to a near design basis seismic event demonstrated that such design provisions can be effective. However, international understanding of the detailed behaviour of nuclear structures in a major seismic event may be enhanced following close examination of data on the condition of structures at the Fukushima-1 site.

371 As in Japan, most nuclear sites in the UK are on the coast. However, earthquakes of the size experienced in Japan are well beyond the predicted extreme hazards for the UK, and a Department for Environment, Food and Rural Affairs (Defra) study following the 2004 Boxing Day tsunami

concluded that tsunami risk to the UK was extremely small. That study took all potential sources into consideration and found that the most likely event to affect the UK would be a repeat of the 1755 tsunami that destroyed the city of Lisbon; such an event would result in waves around the south west of England no higher than a typical high tide combined with a weather-induced storm surge (i.e. 2m on top of a high tide). The probabilities of extreme water levels around the UK have recently been re-estimated by an Environment Agency study, using statistical techniques that account for the joint occurrence of storm surges and high tides. The Defra tsunami risk study found that the sea levels from a Lisbon-type event were associated with the so-called 100-year return period (i.e. a sea level which on average occurs once every 100 years). In comparison the guidance for siting and protecting nuclear installations is a 10,000-year return period.

372 Questions have also been raised on the advisability of siting new nuclear power stations within areas of a designated flood risk – such as is proposed for a UK Flood Zone 3. Our considerations of the effects of severe flooding on the Fukushima-1 site, in contrast to the less problematic effects of flooding on the Fukushima-2 site, do not lead us to alter our view that a risk of flooding of unprotected land is not, in itself, a reason for excluding construction of nuclear plants in such areas. However, in the event that a specific plant was proposed for a particular site, an examination of the flooding risk may impact on the layout and design of plant, and flooding protection of the site. In principle, it should be practicable by design to accommodate such flooding as might be experienced on a particular UK location such as a Flood Zone 3. The issue will be encompassed by the flooding design basis, and for proposed new nuclear power stations in the UK this will be subject to detailed regulatory scrutiny by ONR and Environment Agency.

373 Extreme flooding can also arise from other causes such as catastrophic failures of dams, or from sea-level rise and severe weather due to the more gradual change in our climate. We believe that dam failure is not an issue for UK nuclear sites, present or planned. With regard to climate change, the UK's nuclear regulatory regime requires periodic reviews of the safety of each nuclear facility and these cover such matters. Additionally, consideration of the impact of climate change is a requirement for the safety case for any proposed nuclear power stations.

374 These views are supported by a recent note (see Annex F) by the environment agencies on flooding risks around nuclear licensed sites in England, Scotland and Wales.

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.

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.

375 We, together with colleagues in the environment agencies and other agencies, will undertake our own independent review in this area. Learned institutions could play an important role in this work.

Capability for Effective Off-site Emergency Countermeasures

376 Although the details involved in Japanese authorities' response to the accident at Fukushima are not certain at present, it is apparent that they have demonstrated the feasibility of implementing timely and effective countermeasures for a large population, despite major disruption of the infrastructure. This demonstrates the importance of adequate prior emergency planning and organisation for dealing with the consequences of a major nuclear accident.

377 There is a relationship between the capabilities for off-site emergency response, timescales of accidents and disposition of nuclear facilities relative to the surrounding population.

378 Irrespective of a plant's design and its assessed levels of safety[g], the UK adopts a prudent approach to the siting of new designs of nuclear power plants, and this is expressed in the form of a semi-urban criterion. This places constraints on the allowable population in the vicinity of nuclear reactor. It ensures that in the unlikely event of a major radiological release the numbers of people that may be affected would be limited, and facilitates the implementation of any necessary emergency countermeasures to protect that population.

379 In Japan, the authorities initially invoked a series of off-site evacuation and countermeasures as described above. Some further consideration appears to be given to more relocation on the basis of the prospect of prolonged exposure to deposited radioactivity. The emergency countermeasures distances adopted are consistent with siting practice in the UK.

380 The reactors involved in the accident at the Fukushima-1 site were designed in the 1960s. Since then much work has been undertaken by reactor designers to improve nuclear safety further, taking on board lessons learnt from the Three Mile Island accident in the USA and Chernobyl in the Ukraine, as well as advances in understanding and new technology. As a result the new reactor designs currently under consideration for the UK, (Generation 3+)[h], are significantly more robust than the designs at Fukushima. These are aimed at minimising the likelihood of a major accident and, in the unlikely event of such an accident, to prevent significant quantities of radioactive material being released. The modern containment structures of such designs take into account extreme external events including aircraft impact.

381 Such factors lead us to conclude that given the reactor designs being considered for deployment in the UK, it is unlikely that the pre-planned emergency countermeasure zones around new power reactor plants in the UK would need to be any greater than for existing sites.

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

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[g] AGR reactors were conceived on the basis that they were to be built in populated areas. The containments of modern PWRs are intended to prevent any significant release.

[h] Generation 3+ reactors offer significant improvements in safety and economy over earlier designs. AP1000™ and UK EPR™ are Generation 3+ reactor designs.

Multi-reactor Sites

382 A contributory factor in the progression and handling of the Fukushima-1 accident was the proximity of the reactor units to each other. The complications included:

- An explosion in one reactor unit impinging on the safety of a neighbouring reactor unit (this appears to be the case with Reactor Unit 3 causing damage to the adjacent Reactor Unit 4 building including possibly to the Reactor Unit 4 fuel storage pond).
- An event at one reactor unit causing high radiation levels such that actions by personnel to secure the safety of another reactor unit were not possible or were made significantly more difficult (several times during the Fukushima-1 accident workers were withdrawn).
- The ability of a limited work force to deal with concurrent events on the same site.

383 Such considerations have raised questions about the continued advisability of constructing new multi-reactor sites in the UK. The previous discussion on the containment and other design features of new reactors being considered for the UK is relevant as these features should severely limit the risks of a major accident occurring in any one reactor unit. We consider that there is no reason in principle 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.

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

384 A complicating factor in the Fukushima accident was the spent fuel stored on the site, particularly in fuel ponds inside the reactor buildings. In the case of the Reactor Unit 4 pond, there were at least two and half cores worth (1,331 elements) of spent fuel held in the pond located very near to the reactor.

385 In addition, around 6,000 spent fuel elements are held in the main storage pond on site, with further quantities in dry storage casks. These facilities do not appear to have contributed to the problems at the Fukushima site.

386 In the reactor building spent fuel ponds, the operators had employed increased packing density of the spent fuel elements due to decreasing spare capacity in the ponds. Before increasing the packing density in any spent fuel pond, consideration has to be given to criticality accidents and to the fuel pond cooling capabilities, both for normal operation and for accident situations. Increased packing density will also shorten the time available after a loss of cooling accident before the fuel pond begins to boil. This therefore puts greater onus on the reliability of the cooling systems and on operator remedial action in the event that normal cooling is lost.

387 The quantities of spent fuel held at the site may well reflect a wider issue of dealing with spent fuel in Japan when the full operation of the new national reprocessing plant is running behind schedule, and with limited availability of alternative fuel reprocessing facilities across the world. We understand that some consideration is being given in Japan to constructing a centralised spent fuel store away from the coast. In the UK, except for Sizewell B, the existing operating reactors send fuel to Sellafield for storage and reprocessing thus minimising spent fuel storage at sites other than at Wylfa where a dry store is located. Even at Wylfa the quantity of spent fuel stored on site is modest, about 25 percent of a reactor core load, and is generally passively cooled.

388 The individual spent fuel storage ponds in the Fukushima plants are located at height, in close proximity to the reactors. This close proximity clearly presents the possibility of an accident in one part of the plant affecting the other. Given this, there would appear to be good safety reasons to minimise (ALARP) the amount of spent fuel in each such pond, especially when a core’s worth of hot fuel is unloaded at once. In the case of gas-cooled reactors only relatively small amounts of hot fuel are required to be unloaded at any one time. In the UK, this approach would be reinforced through one of our SAPs (No. ENM.6) states:

> *“When nuclear matter is to be stored on site for a significant period of time it should be stored in a condition of passive safety and in accordance with good engineering practice.”*

389 We consider that the UK nuclear industry should consider any new spent fuel strategies employed for its plants to ensure that this principle is fully adopted. There is the possibility that this may enhance the drive for different approaches to spent fuel management in the future with earlier conditioning or treatment into more demonstrably passive safe forms.

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.

390 This may also be usefully considered in the provision of more spent fuel storage at Sizewell B.

Site and Plant Layout

391 It is reported that the back up diesel supply at the Fukushima-1 site survived the severe earthquake as did the electrical switchgear used for distributing off-site power across the site. However, the tsunami rendered both inoperable and it took almost two weeks to restore power supplies to most of the site’s six reactors. At least part of the problem stems from the location of the diesel generators on site and the electrical switchgear in the bottom part of the turbine hall, and the diesel fuel tanks in the path of the tsunami. These systems were thus vulnerable to either the tsunami’s physical impact or the consequential flooding. It is not yet known in what way plant layout differs between the Fukushima-1 site and Fukushima-2 site/plants but it may be that differences exist which would explain some of the disparity in the effects of the tsunami at the two sites.

392 Although design aspects such as these are considered in UK safety assessments, in light of the events at the Fukushima-1 site we consider that reviews of plant and site layout be undertaken both for existing nuclear facilities and for proposed new designs. These reviews should focus on possible modifications or design changes needed to minimise the effects of severe flooding and other extreme external events on the functionality of safety systems, their essential supplies and associated electrical switch gear. Such reviews will need to consider the challenges of protecting

against different hazards, for instance there may be advantages in locating some safety equipment low down to make it more resilient to seismic hazards or against human interventions, but high up to protect it against flooding. This may drive the need for more redundancy to adequately protect against a range of potential events.

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[i] robustness against severe flooding and other extreme external events.

Fuel Pond Design

393 It is not yet known what has caused the reactor ponds, especially Fuel Pond 4, to lose water to the extent that appears to have happened. The amount of water still being pumped into the ponds indicates that at least Reactor Unit 4 Fuel Pond is losing water through some mechanism other than evaporation, e.g. through leakage from structural failure of the pond. The TEPCO roadmap for restoration of the site includes measures to install a supporting structure over the next three months which may indicate concerns about the pond's structural integrity.

394 Examination of some outline process flow drawings for the reactor building pond cooling systems indicates that there are some pipelines penetrate the bottom of the interconnecting structure of the pond. Fractures of these could account for some water loss. There is also the possibility of water loss by siphoning from fractured fully flooded pipes that enter the pond from above.

395 More details are required on the design and condition of the fuel ponds at Fukushima-1 before definitive lessons can be learned in relation to spent fuel pond design. However, we consider it good practice for any new designs of reactor spent fuel ponds for bottom entry penetrations and lines without siphon breaks to be minimised, and any that are necessary are robust to faults to potential faults.

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

396 The Fukushima reactor shut down systems operated effectively in response to the level 9 earthquake as did the secondary cooling systems. This indicates the robustness of seismic design approaches adopted for these Japanese plants. In due course, important insights may be gained from detailed observations of the performance of the reinforced concrete reactor building and containment structures, under both the seismic and subsequent thermal and explosive loading from hydrogen events. This will allow for comparison of actual structural behaviours with analysis and code expectations, and may provide valuable insights into design/analysis for such structures in the future.

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[i] "Adequate" means the risks are reduced so far as is reasonably practicable – the legal requirement.

397 Learning from the effects of earthquakes on conventional plant has been done for many years. However, some of the plant and equipment in nuclear power plants is unique and specialised. This earthquake will be a valuable learning opportunity, and when the relevant information becomes available a review of any implications for UK nuclear facilities should be undertaken as part of the ongoing periodic review for safety.

> **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.**

Flooding

398 Flooding has been considered in the discussion of impact on siting and site/plant layout above. It should be noted that the environment agencies have recently provided an updated summary of the position for sites in England, Scotland and Wales, and this was discussed by the Technical Advisory Panel (TAP) (Annex F).

Other Extreme External Events and Severe Accident Management

399 Some of the above considerations are relevant to other extreme external events including extreme weather, aircraft crash and security related incidents. Such events may have implications for the availability of off-site and on-site safety related supplies. Such events could have common cause effects, and indicate increased requirements for segregation and diversity of safety systems and essential supplies, and implications for plant and site layout. Vulnerability assessments to determine suitable barriers to protect[j] against terrorist attack should also take account of such matters. We therefore consider that in addressing the recommendations identified elsewhere in this report in relation to seismic and tsunami hazards consideration should also be given to the implications for other extreme hazards.

> **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.**

Loss of Heat Sink

400 Heat removed from the reactor to keep it cool when shut down has to be dispersed elsewhere. Normally, for a site close to the sea this is done by pumping sea water through a heat exchanger with the heat being dispersed to the open sea, which forms the ultimate heat sink. There are reports that for a period the reactor heat sink pumps for reactor units at the adjacent site, Fukushima-2, failed due to them being overwhelmed by flooding and urgent operator action was needed to restore this capability. This again points to the need to consider the layout of all safety related plant and their protection against extreme events as part of the design and safety case. This consideration is encompassed by the conclusions and recommendations above.

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[j] Nuclear safety, security and safeguards control can be viewed similarly in that the same principles are involved in determining adequate protection (such as multiple independent barriers, diversity, segregation, no single point failure mode, etc). This is one of the reasons why the regulation of such matters in the UK is covered by one body – ONR.

Off-site Electricity Supplies

401 Grid supplies were lost when the earthquake struck the area around Fukushima, with later grid supply interruptions during aftershocks. The reactor shutdown systems and emergency cooling systems survived the initial earthquake but problems arose at the Fukushima-1 site because of prolonged unavailability of electrical power. Unless provisions are made for long-term independent on-site emergency electrical supplies then assurance of safety on the site depends on the timely restoration of a reliable off-site grid supply (unless alternate means of supplying power from off-site are sourced). The anticipated reliability of the UK national grid is taken into account during the design and safety assessment of UK nuclear plant. However, we consider that the grid's robustness and potential for extended unavailability in severe hazard conditions should be re-evaluated in light of the Fukushima accident.

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

402 As with many nuclear plants world-wide, the on-site emergency electrical supplies at the Fukushima-1 site involved diesel generators and back-up batteries. As well as reviewing plant layouts, the protection against flooding and the interplay between on-site and off-site electrical supplies, consideration should also be given to the provision of additional, diverse means of providing robust long-term electrical suppliers independent of the grid for emergency cooling, emergency control and instrumentation systems. Such dedicated supplies may be located on or near the site with suitable robust connections.

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

403 The circumstances of this accident were such that innovative and untried means of supplying coolant into the reactors and affected fuel ponds have been necessary for some weeks. This resulted in thousands of tonnes of contaminated water accumulating on site with some leaking into the sea and some being discharged purposely into the sea to release tank capacity. At the time of writing, normal water re-circulation systems are still inoperative in Reactor Units 1 to 4 at Fukushima-1.

404 In the period before other cooling could be established at the Fukushima-1 site, steam pressures rose in the affected reactors as water levels dropped, exposing the hot fuel. With exposure of the fuel, temperatures were reached where the zirconium fuel cladding reacted with steam to produce a hydrogen-enriched atmosphere. This meant that when the operators vented the reactor vessels to relieve steam pressure, the vented gases from the reactor eventually reached other parts of the reactor building where they mixed with air and created explosive mixtures.

405 In the absence of fresh water supplies, the operators used sea water injection into the pressure vessels to provide fuel cooling. Although this seems a sensible approach, it did lead to concerns about its prolonged use because of potential for pressure vessel corrosion and possible impaired

heat transfer with salt deposition on the fuel. Fresh water was eventually brought in on US Navy barges.

406 An important feature of many reactor designs is the ability to have a “natural” cooling capability if forced circulation of coolant through the core fails. The gas-cooled reactor cores in Advanced Gas-cooled Reactors (AGR) and Magnox reactors operating in the UK can be cooled by natural circulation of the coolant (carbon dioxide) driven by convection. This requires the containment boundary to be maintained as well as feeding water to a single in-reactor heat exchanger and then the heat taken away to the ultimate heat sink, e.g. the sea. Additionally, the carbon dioxide coolant in AGR and Magnox reactors does not significantly change heat transfer characteristics with increasing temperatures as happens in a water-cooled reactor where the water can flash to steam. In AGRs and Magnox reactors the requirements for emergency pressure vessel venting are therefore much reduced. 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).

407 Additionally, the cores of the Magnox and AGR reactors operating in the UK have much 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.

408 Although the gas-cooled reactors in the UK have these beneficial differences and the natural cooling capability and coolant can be topped up from on-site gas stores, given the experience in Japan, we consider that it would be prudent to review the capability for coolant replenishment under severe fault conditions resulting from widespread natural hazards (when additional supplies to the site may be curtailed for some time). Contingency plans could then be revised as necessary.

409 For Sizewell B, decay heat is removed by the Main Feed Water System, the Motor Driven Auxiliary Feed Water System or the diverse Turbine Driven Feed Water System. The heat sink for the post-trip cooling systems at Sizewell B is provided by the Essential Service Water system or the Reserve Ultimate Heat Sink (air cooled). This provides one of the world’s most robust PWR cooling systems.

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.

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 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.

410 For the Fukushima-1 site there was a need to adopt diverse and unplanned means to provide coolant for the fuel ponds given the lack of normal water supplies and heat exchangers, and damage caused by the hydrogen explosions and fires. The use of articulated pumping equipment normally used to deliver concrete appears to have been particularly useful. In the UK, although there are contingency provisions for pond water make up, we consider that these should be reviewed in light of the experience in Japan to determine whether they can and should be

enhanced. It is noted that for the UK fleet of AGR and Magnox reactors there is more limited storage of spent fuel on site as it is shipped to Sellafield.

Recommendation 20: The nuclear industry should review 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.

Control and Containment – Combustible Gases

411 As a design principle, the production of combustible gases within the plant should be minimised both under normal operating conditions and under fault conditions. Although high radiation fields will generate hydrogen from radiolysis of water, these amounts are small and under normal conditions these are relatively easily and safely dealt with by the plant design.

412 However, far greater quantities can be generated by chemical reactions under accident conditions such as that between zirconium fuel cladding and steam on loss cooling in BWR cores. Provision for this eventually has to be made in the design, as is done in the PWR designs. Gas-cooled reactors cannot generate hydrogen in this way and it is reported that any carbon monoxide generated will not lead to explosive concentrations.

413 In the case of the Fukushima event there has been some speculation that the routes for venting gases from the reactor had not been, perhaps, updated in line with increased worldwide knowledge about the potential consequences of venting in BWR accident conditions. We do not yet know enough about the particular design features of the Fukushima-1 reactor units, although it is certainly possible that inadequacies in the venting routes may have featured in the devastating explosions that were seen in Reactor Units 1 and 3. Additionally, it appears that an explosion occurred in the suppression pool torus of Reactor Unit 2, possibly breaching the primary containment. This may indicate that more attention should have been given in the design and safety assessment to the robustness of the Fukushima-1 reactor unit reactor pressure vessel venting routes. Early light water reactor containments, both BWR and PWR, were not specifically designed to manage severe accident conditions. Modern reactor containments are however, specifically designed to take such accident conditions into account.

414 In the UK, filtered containment venting was considered for Sizewell B but on balance were decided against to provide a more reliable containment.

415 It is worth noting that for some non-reactor nuclear plants in the UK, hydrogen can be generated in significant quantities under fault conditions. This applies particularly to Magnox cladding wastes which are stored in vaults under water at Sellafield. These wastes arise in the reprocessing of Magnox spent fuel when the cladding is stripped off the inner bar of uranium. In the process some of the spent fuel adheres to the Magnox swarf[k] making the resultant waste very radioactive. Some years ago the practice of storing Magnox swarf under water was stopped and since then the swarf has been directly encapsulated into concrete. However, the existing vaults of Magnox swarf at Sellafield are still to be decommissioned. These vaults now include several provisions to prevent combustible concentrations of hydrogen being created. These are cooling the vaults' contents and inerting their atmospheres. Additionally, it is expected that over the years much of the Magnox swarf will have reacted slowly with the water so making it relatively inert. However, great care will

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[k] "Swarf" refers to fragments of the Magnox cladding that are peeled off when the fuel is decanned.

still need to be exercised when intrusive decommissioning activities of these facilities are undertaken.

416 Given the experience at the Fukushima-1 site we consider it is prudent to review whether the systems for venting containments of potentially significant concentrations of combustible gases are sufficiently robust.

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.

Fuel

417 Reactor Unit 3 had some mixed oxide (MOX) fuel in the core, whereas the other affected reactors did not. Fresh MOX fuel contains around 10 percent plutonium oxide with the rest made up of natural or depleted uranium oxide. The percentage reduces as the plutonium is burnt in the reactor. In most operating power reactors the fuel contains only uranium oxide, but as it is burnt up some converts to plutonium (typically up to between 1 and 2 percent when discharged).

418 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. Regardless of whether or not reactors are fuelled with MOX, the main radioactive nuclides that dominate the health impact of nuclear reactor accident releases are iodine-131 and caesium-137. Plutonium releases from the oxide fuel are much lower and have a much lower relative importance in such accidents.

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.

Emergency Control and Indication Centres, Instrumentation and Communications

419 While it is known that all the main control rooms of Fukushima-1 Reactor Units 1 to 4 were rendered inoperable for several days, we have little information at present on whether there were alternative emergency control centres available to the operators, and what remote instrumentation and control was in place. There are indications that such facilities were not sufficient and that some of the normal instrumentation was not robust enough in the circumstances of the accident. In the UK, emergency control and indication centres are situated on nuclear power plant sites and are intended to be robust during accidents. However, they have limited capabilities for severe accidents and given the circumstances of the Fukushima accident we consider a review should be undertaken. This should also look at the provision of secure communications both on and off the site, and among all government agencies that might be involved, taking account of lessons from other severe non-nuclear events.

Recommendation 22: The UK nuclear industry should review the provision of on-site 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

420 With regard to human factors, there is the potential to learn many lessons 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.

421 Although further information and analysis will be needed before all lessons regarding human actions can be determined, we consider that in the meantime reviews of severe accident management plans and training at UK nuclear facilities should be commenced to ensure that they are fully up to date. These reviews should include some consideration of the emotional aspects of dealing with severe accidents, especially in the circumstances where plant workers' homes and families may be affected by the direct cause such as extreme weather or flooding.

422 Additionally, there may be benefit in considering some cultural and organisational aspects, including the need for exemplary leadership.

423 This accident occurred during day time. If it had taken place during the night then it is likely there would have been fewer staff on site, especially supervisory, engineering and maintenance staff. This could have complicated the response to the accident.

424 Such physical, organisational, cultural and emotional issues should be considered in reviewing the severe accident arrangements and training.

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.

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

425 Many of the above considerations are intrinsically linked to nuclear plant safety cases. The events at Fukushima have highlighted a number of issues that should be reviewed for each UK plant and, if necessary, provided for in revisions of the safety case. An acceptable safety case will be required to provide an appropriate basis for any changes to plant and arrangements for severe accidents. There is a particular need to consider longer term analysis of fault sequences taking account of the development of the accident sequence over time and the potential loss of services, such as cooling and electricity, as well as the potential for repair and recovery to a stable state.

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.

Taking the Recommendations Forward

426 We note that in response to a request from the Council of the European Union, work is underway to develop "stress tests" (www.wenra.org) for nuclear facilities to test the barriers against severe accidents beyond design basis assumptions. National regulators will require operators to undertake such tests and report back. The national regulators in turn will independently assess the responses. In the UK we would then require any identified improvements to be implemented, in line with the ALARP principle. The timescale for this work is not yet confirmed but is unlikely to be completed much before the end of the year.

427 There may well be overlaps between these "stress tests" and the recommendations in this report. Thus, once the details of the "stress tests" are known then it is recommended that the nuclear industry produce a common plan for responding to the requirements, and the recommendations in this report, and that this plan is published. Many of our recommendations are framed in the form of areas to review to identify possible improvements. 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 be identified. We will assess progress of such work and any emerging proposals and report on it in our final report. Given the timescales for the "stress tests", we will publish a supplement to our final report to take account of their outcome.

Recommendation 26: A response to the various recommendations in this 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.

ANNEX A: INTERNATIONAL CO-OPERATION

The Secretary of State's request identified the need for co-operation on an international scale in responding to his request. There was existing good co-operation between nuclear regulators worldwide and through various international nuclear bodies. This latter grouping includes:

- The International Atomic Energy Agency (IAEA) (www.iaea.org)
- The OECD's Nuclear Energy Agency (NEA) (www.oecd-nea.org)
- European Council's European Nuclear Safety Regulators Group (www.ensreg.org)
- The Western European Nuclear Regulators Group (www.wenra.org)

Further information on the above bodies is available via their websites. All have had meetings (or plan meetings in the near future) at which the Fukushima-1 accident and lessons to be learnt were discussed. Additionally, from 1 April until 14 April 2011 the tri-annual Review Meeting of the Convention on Nuclear Safety was held and special attention was paid to the topic of this report as reported at http://www-ns.iaea.org/downloads/ni/safety_convention/cns-summaryreport0411.pdf. ONR staff play an active part in these organisations, including the Chief Inspector, see Annex E.

In addition, ONR has close bilateral links with other nuclear regulators, in particular the USA Nuclear Regulatory Commission (USNRC) and the French Autorité de Sûreté Nucléaire (ASN). These links have been very useful in the immediate response to the incident and in co-ordinating work.

The Chief Inspector has also had bilateral discussions with several other chief nuclear regulators from around the world and with the Director Generals and senior staff of the IAEA and NEA, and similarly with the Director General for Energy of the European Council.

Of particular note coming out of such meetings and discussions are:

- Agreements among major nuclear regulators to share information about their national reviews.
- The development of European Council based "stress tests" (latest version is available on the WENRA website www.wenra.org) for nuclear facilities in Europe the based on the emerging issues to be completed by the end of the year.
- A special conference under the NEA in Paris of nuclear regulators and stakeholders in early June.
- A ministerial conference under the IAEA later in June.
- An extraordinary Review Meeting of the Convention on Nuclear Safety to review contracting parties responses to the Fukushima-1 accident in August 2012.

Additionally, the Chief Inspector has been invited to lead an IAEA high level team of international nuclear experts to conduct a fact finding mission to Japan, initially to feed into the IAEA ministerial conference.

Such co-operation has greatly enhanced our ability to respond to the Fukushima-1 accident and prepare this report. It will also be very useful in preparing our final report, greatly enhancing our understanding of the details and areas for possible improvements to nuclear safety.

ANNEX B: HISTORICAL GENERAL RISKS ASSOCIATED WITH VARIOUS HAZARDS

The following tables have been extracted from the HSE publication *Reducing Risks, Protecting People*, which can be found at: http://www.hse.gov.uk/risk/theory/r2p2.pdf.

Table B1: Annual Risk of Death for Various United Kingdom Age Groups Based on Deaths in 1999 (Annual Abstract of Statistics, 2001/Health Statistics Quarterly – Summer 2001)

Population group	Risk as annual experience	Risk as annual experience per million
Entire population	1 in 97	10,309
Men aged 65-74	1 in 36	27,777
Women aged 65-74	1 in 51	19,607
Men aged 35-44	1 in 637	1,569
Women aged 35-44	1 in 988	1,012
Boys aged 5-14	1 in 6,907	145
Girls aged 5-14	1 in 8,696	115

Table B2: Annual Risk of Death for Various Causes Averaged Over the Entire Population

Cause of death	Annual risk	Basis of risk and source
Cancer	1 in 387	England and Wales 1999 (1)
Injury and poisoning	1 in 3,137	UK 1999 (1)
All types of accidents and all other external causes	1 in 4,064	UK 1999 (1)
All forms of road accident	1 in 16,800	UK 1999 (1)
Lung cancer caused by radon in dwellings	1 in 29,000	England 1996 (2)
Gas incident (fire, explosion or carbon monoxide poisoning)	1 in 1,510,000	GB 1994/95-1998/99 (3)
Lightning	1 in 18,700,000	England and Wales 1995-99 (4)

Notes: *(1) Annual Abstracts of Statistics (2001)*
(2) National Radiological Protection Board (1996)
(3) Health and Safety Executive (2000)
(4) Office of National Statistics (2001)

Table B3: Annual Risk of Death from Industrial Accidents to Employees for Various Industry Sectors (Health and Safety Commission, 2001)

Industry sector	Annual risk	Annual risk per million
Fatalities to employees	1 in 125,000	8 (1)
Fatalities to the self-employed	1 in 50,000	20 (1)
Mining and quarrying of energy producing materials	1 in 9,200	109 (1)
Construction	1 in 17,000	59 (1)
Extractive and utility supply industries	1 in 20,000	50 (1)
Agriculture, hunting, forestry and fishing (not sea fishing)	1 in 17,200	58 (1)
Manufacture of basic metals and fabricated metal products	1 in 34,000	29 (1)
Manufacturing industry	1 in 77,000	13 (1)
Manufacture of electrical and optical equipment	1 in 500,000	2 (1)
Service industry	1 in 333,000	3 (1)

Notes: *(1)* *Health and Safety Commission, Health & Safety Statistics (1996/97, 1997/98, 1998/99 & 1999/2000/2001) published by HSE Books.*

Table B4: Average Annual Risk of Injury as a Consequence of an Activity

Type of accident	Risk	Basis of risk and source
Fairground accidents	1 in 2,326,000 rides	UK 1996/7-1999/00 (1)
Road accidents	1 in 1,432,000 kilometres travelled	GB 1995/99 (2)
Rail travel accidents	1 in 1,533,000 passenger journeys	GB 1996/97-1999/00 (3)
Burn or scald in the home	1 in 610	UK 1995-99 (4)

Notes:
(1) Tilson and Butler (2001)
(2) Department of Environment, Transport and the Regions – Transport Statistics (2000)
(3) Health and Safety Executive (2001)
(4) Department of Trade and Industry and Office of National Statistics (2001)

Table B5: Average Annual Risk of Death as a Consequence of an Activity

Activity associated with death	Risk	Basis of risk and source
Maternal death in pregnancy (direct or indirect causes)	1 in 8,200 maternities	UK 1994-96 (1)
Surgical anaesthesia	1 in 185,000 operations	GB 1987 (2)
Scuba diving	1 in 200,000 dives	UK 2000/01 (3)
Fairground rides	1 in 834,000,000 rides	UK 1989/90-2000/01 (4)
Rock climbing	1 in 320,000 climbs	England and Wales 1995-2000 (5)
Canoeing	1 in 750,000 outings	UK 1996-99 (6)
Hang-gliding	1 in 116,000 flights	England and Wales (7)
Rail travel accidents	1 in 43,000,000 passenger journeys	England and Wales 1997-2000 (8)
Aircraft accidents	1 in 125,000,000 passenger journeys	GB 1996/97 - 1999-2000 (9)

Notes: *(1) NHS Executive (1998)*
(2) Lunn and Devlin (1987)
(3) Based on assumption of 3 million dives per year. British Sub-Aqua Club (2001)
(4) Based on estimated 1 billion rides per year. Tilson and Butler (2001)
(5) Based on the assumption that there is a total of 45,000 climbers making an average of 20 climbs per year each. Mountain Rescue Council (2001)
(6) Based on the assumption that there are 100,000 whitewater canoeists making an average of 30 outings per year each. Drownings in the UK, RoSPA (1999)
(7) British Hang-gliding and Paragliding Association (2001). Based on the assumption that each member makes an average of 50 flights per year.
(8) Health and Safety Executive (2001)
(9) Civil Aviation Authority (2001)

ANNEX C: TYPICAL EXPOSURES TO IONISING RADIATION FROM DIFFERENT ACTIVITIES

Source of Exposure	**Dose**
Dental X-ray	0.005 mSv
135g bag of Brazil nuts	0.01 mSv
Chest X-ray	0.02 mSv
Transatlantic flight	0.07 mSv
Nuclear power station worker average annual occupational exposure	0.2 mSv
UK annual average radon dose	1 mSv
CT scan of the head	1.4 mSv
UK average annual radiation dose	2.7 mSv
USA average annual radiation dose	6.2 mSv
CT scan of the chest	6.6 mSv
Average annual radon dose to people in Cornwall	7.8 mSv
Whole body CT scan	10 mSv
Annual exposure limit for nuclear industry employees	20 mSv
Level at which changes in blood cells can be readily observed	100 mSv
Acute radiation effects including nausea and a reduction in white blood cell count	1000 mSv
Dose of radiation which would kill about half of those receiving it in a month	5000 mSv

Figures taken from HPA website (www.hpa.org.uk).

ANNEX D: EMERGENCY ARRANGEMENTS IN THE UK

International Conventions and Agreements

The Convention on Early Notification in the Event of a Nuclear Accident or Radiological Emergency (Ref. D3) describes the arrangements established by the International Atomic Energy Agency (IAEA) under which any signatory country that operates nuclear installations is obliged to inform the IAEA immediately of an accident which could have consequences outside the country's own borders. The UK is a signatory to the Convention and as such has established arrangements to inform IAEA should such events occur in the UK.

The UK has also established bilateral agreements with the Danish, Dutch, French, Irish, Norwegian and Russian governments which provide for early notification and provision of information on the course of events occurring at the accident site.

UK Approach to Civil Nuclear Emergency Preparedness and Response

The UK's arrangements for emergency preparedness and response for a radiological emergency at a UK nuclear installation are consistent with the integrated planning concept described in *Preparedness and Response for a Nuclear or Radiological Emergency*, GS-R-2 published in 2002 (Ref. D1).

In the UK, the authority for developing, maintaining and regulating arrangements for preparedness and response for a nuclear or radiological emergency is established through the following acts and regulations:

- Health and Safety at Work etc. Act (HSWA) 1974 (Ref. D5)
- Radiation (Emergency Preparedness and Public Information) Regulations 2001 (REPPIR) (Ref. D7)
- Civil Contingencies Act (CCA) 2004 (Ref. D14)
- Nuclear Installations Act 1965 (as amended) (Ref. D6)
- Ionising Radiation Regulations (IRR) 1999 (Ref. D10)

To coordinate the multi-agency response in the UK, the lead government department in England and Wales (The Department of Energy and Climate Change (DECC)) set up the Nuclear Emergency Planning Liaison Group (NEPLG) to provide a forum to discuss national issues. Members include representatives of the nuclear operators, police, fire service, local authority emergency planning officers, nuclear regulators and Government departments and agencies which would be involved in the response to an emergency.

NEPLG provides a forum for discussing common problems, exchanging information and experience and agreeing improvements in planning, procedures and organisation. NEPLG has issued consolidated guidance (Ref. D2) for planning for a civil nuclear emergency. NEPLG also reviews results of off-site emergency exercises to ensure that important lessons are learned from those exercises and put into practice.

Emergency Planning Principles

The principles which form the basis of emergency planning in the UK are described in the HM Government publication *Emergency Response and Recovery, Non statutory guidance to complement Emergency Preparedness* (Ref. D4). Civil protection in the UK is based on the concept of integrated emergency management. Under integrated emergency management, both preparation for and response to emergencies focuses on the consequences of events rather than their causes. There is, therefore, a generic framework for responding to and recovery from emergencies whatever the scenario.

The arrangements established to respond to nuclear emergencies are consistent with those applied in response to any major emergency and provide a framework for all organisations to deliver a co-ordinated response. The scale of the UK response to a nuclear emergency will be proportional to the magnitude and the likely impact on the public and the environment. Hence, close co-operation between all organisations will be required in order to minimise any impact.

In the UK the Regulatory Body is made up of a number of key organisations /agencies. These are the Office for Nuclear Regulation (ONR) an agency of the Health and Safety Executive's (HSE), the Environment Agency, the Scottish Environment Protection Agency (SEPA), the Health Protection Agency (HPA) and the Food Standards Agency (FSA).

Emergency Preparedness and Response for a Radiological Emergency at a Civil UK Nuclear Installation

The precautions taken in the design and construction of nuclear installations in the UK, and the high safety standards in their operation and maintenance, reduce to an extremely low level the risk of accidents that might affect the public. However, as a final line of defence, all nuclear installation operators and relevant local authorities prepare, in consultation with the emergency services and other bodies, emergency plans for the protection of the public and their workforce in a nuclear emergency. These are regularly tested in exercises under the supervision of ONR.

Public Protection Countermeasures

HPA was established on 1 April 2005 under the Health Protection Agency Act 2004 (Ref. D15) as a non-departmental public body, replacing the HPA Special Health Authority and the National Radiological Protection Board (NRPB), and with radiation protection as part of health protection incorporated in its remit.

The Health Protection Agency - Radiation Protection Division's (HPA-RPD) statutory functions include:

- the advancement of the acquisition of knowledge about protection from radiation risks; and
- the provision of information and advice in relation to the protection of the community (or any part of the community) from radiation risks.

HPA – RPD has specified Emergency Reference Levels (ERL) for guidance on countermeasures in response to a nuclear accident. The ERLs currently set for early countermeasures were promulgated in 1990.

The principal off-site countermeasures in the early stages of a nuclear emergency that can be taken to reduce the radiation doses to members of the public are sheltering and evacuation. In addition, for operating nuclear power reactors, radiation doses from the intake of radio-iodine can be reduced by iodine prophylaxis (the taking of potassium iodate tablets).

Sheltering means staying indoors with doors and windows closed. It provides some protection from radiation emitted by airborne and deposited radioactivity and from inhalation of airborne radioactivity.

Iodine prophylaxis is the administration of non-radioactive iodine in tablet form. Escape of radioactive iodine is one of the most important radiological consequences of an accident at a nuclear power reactor. Administration of stable iodine reduces the uptake of radioiodine to the thyroid gland, by diluting it with non-radioactive iodine. For maximum effect the tablets need to be taken shortly before any exposure to radioiodine occurs, hence planned pre-distribution within most UK emergency planning zones is undertaken. Once stable iodine has been administered it will be effective for 24 hours, hence it is important that it is taken neither too early nor too late.

Where the magnitude, timing and duration of a release is uncertain but suggests that evacuation may be needed then evacuation should be recommended. Local authorities will establish rest centres for evacuated residents as they would for any type of emergency situation.

HPA's Centre for Radiation, Chemical and Environmental Hazards HPA-CRCE) is undertaking a project to update and consolidate its advice on radiation emergencies and recovery. Two of NRPB's publications (NRPB, 1990, Ref. D23 and NRPB, 1997a, Ref. D24) gave general advice on Emergency Reference Levels (ERL), how to apply them in the development of emergency plans and how to use them in the event of an accident. A third publication (NRPB, 1997b, Ref. D25) presented advice on intervention for recovery after accidents. This provided a framework for developing protective strategies in the longer term following an accidental release of radionuclides to the off-site environment.

In 2007, the International Commission on Radiation Protection in its Publication 103 (ICRP, 2007, Ref. D26) published a set of recommendations to update, consolidate and replace the Commission's previous 1990 Recommendations. The Commission's advice was further elaborated for emergency exposure situations in Publication 109 (ICRP, 2008, Ref.D27) and for existing exposure situations in Publication 111 (ICRP, 2009, Ref. D28). The new guidance given in these documents represents a marked change in approach and is the main driver for updating and consolidating UK emergency and recovery advice, where it is deemed necessary.

Over the next 18 months, HPA will be:

- Investigating the impact of replacing ERLs based on averted dose by reference levels of residual dose for emergency exposure situations, as recommended by ICRP.
- Reviewing and seeking feedback on current practices for sheltering and evacuation and updating modelling assumptions and advice accordingly.
- Considering the impact of slow, long duration, low level releases on advice to shelter as well as prolonged warning times ahead of the release.
- Developing guidance on the withdrawal of emergency countermeasures.
- Investigating the impact of applying reference levels for annual dose in the 1mSv – 20 mSv range for existing exposure situations, on the development of a recovery strategy.
- Updating advice for the UK on the pre-distribution and use of stable iodine, in the light of updated World Health Organisation (WHO) advice.

Organisation

The organisation that would be established in the event of a nuclear emergency occurring at a licensed nuclear site and the relationships that would be established to deliver a co-ordinated multi-agency response are shown in general terms in **Figure D1:**, **Figure D2:** and **Figure D3:** covering the interface between National, Local and Site Responders, the organisation at the Strategic Coordinating Centre (SCC), and the organisation of the nuclear emergency briefing rooms in London and Scotland.

Figure D1: Interface between National, Local and Site Responders

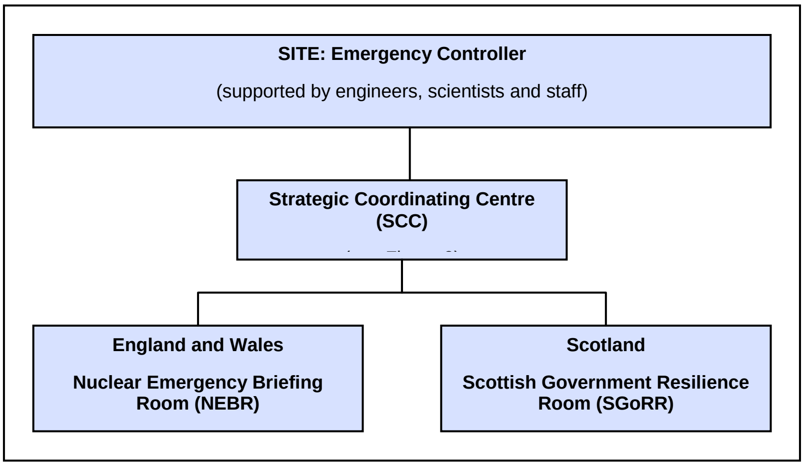


Figure D2: Organisation at Strategic Co-ordinating Centre

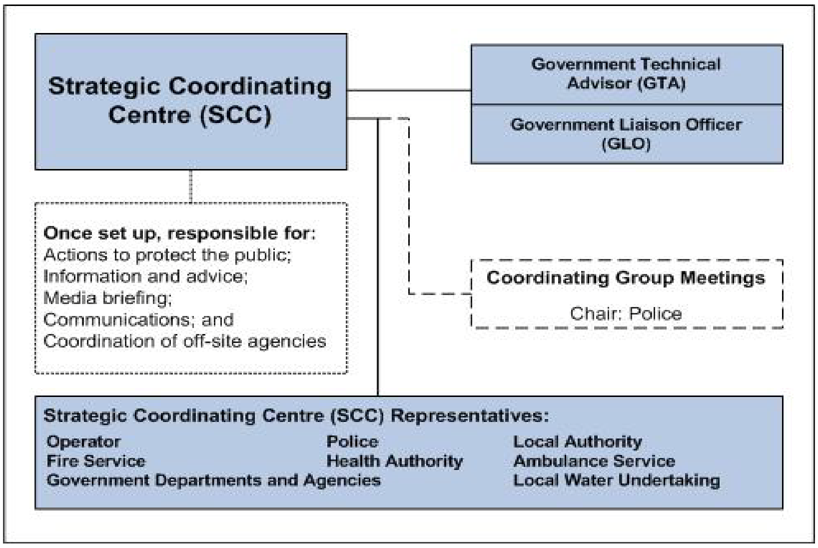
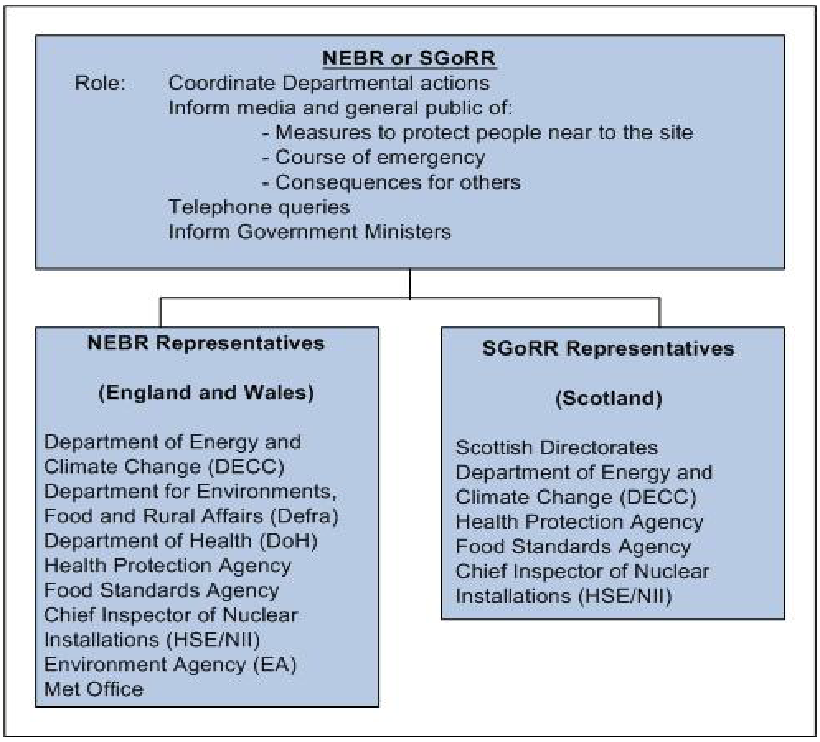


Figure D3: Organisation at Nuclear Emergency Briefing Room (NEBR) and Scottish Government Resilience Room (SGoRR)



National Co-ordinating Authority

The Home Secretary has overall Ministerial responsibility for safety and security, and hence for emergency preparedness and response. Supporting the Home Secretary, lead Ministers in Lead Government Departments are nominated to co-ordinate preparedness and response activities to foreseeable emergencies that could affect the population on the basis that they have day-to-day policy oversight or statutory responsibility for the sector of the national infrastructure that may be affected in an emergency (Refs D16 and D17).

DECC co-ordinates emergency preparedness policy at national level, as the lead government department on arrangements for response to any emergency with off-site consequences from a licensed civil nuclear site in England and Wales. In the event of an emergency at a civil nuclear site in Scotland, the lead Government department responsibility and the main national coordinating role would fall to the Scottish Government. DECC would still be responsible for briefing the Westminster Parliament and the UK's international partners.

Co-ordination of Emergency Response

The UK aims to ensure that it is equipped and prepared to respond to the most unlikely event of an emergency at a nuclear site. The police, working in conjunction with other emergency services, expert bodies, and local and national agencies, would coordinate any response effort locally. The Lead Government department would co-ordinate the response at national level; it would brief Ministers and the

UK's international partners, and be the main source of information at national level to the public and the media. These arrangements are exercised at regular intervals by all the organisations concerned.

Plans and Procedures

In order for an Emergency Plan to be prepared, Detailed Emergency Planning Zones (DEPZ) are established around nuclear installations where there is the potential for an off-site release of radioactivity that would require implementation of the countermeasures described above. These zones are defined based on the most significant release of radiation from an accident which can be reasonably foreseen. REPPIR requires that these plans must be capable of being extended using general contingency plans to deal with a larger, even less likely accident. This is known as the "concept of extendibility".

The radius of the DEPZ differs across UK nuclear installations due to the differences in the nature of operations on the site and the different "reasonably foreseeable" accidents that have been identified.

The requirements for the preparation and testing of emergency plans are principally covered by the Site Licence, which includes a number of Licence Conditions, issued to a site under Nuclear Installations Act 1965 (as amended) (Ref. D6) and REPPIR (Ref. D7) . These are both regulated by ONR.

Training, Drills and Exercises

The principal on-site regulatory tool is Licence Condition 11 which requires rehearsal of the arrangements to ensure their effectiveness. The principal regulatory tool for the off-site component of the Emergency Plan is REPPIR (Ref. D7).

Emergency arrangements are tested regularly under three categories known as levels 1, 2 and 3. Level 1 exercises are held at each nuclear installation-site once a year and concentrate primarily on the operator's actions on and off the site. Level 2 exercises are aimed primarily at demonstrating the adequacy of the arrangements that have been made by the local authority to deal with the off-site aspects of the emergency.

From the annual programme of level 2 exercises one is chosen as a level 3 exercise to rehearse not only the functioning of the SCC but also the wider involvement of central government, including the exercising of the various government departments and agencies attending the Nuclear Emergency Briefing Room (NEBR) (for England and Wales) in London, or the Scottish Government Resilience Room (SGoRR) in Edinburgh.

Quality Assurance Programme

Lessons learned from this site (Level 1), local (Level 2) and national (Level 3) exercise programme are reviewed and any actions requiring improvement to emergency facilities, equipment, procedures, training, etc are identified and actioned.

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D16 Central Government Arrangements for Responding to an Emergency, Concept of Operations, 31st March 2005.

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D18 Food Standards Act 1999, http://www.opsi.gov.uk/acts/acts1999/ukpga_19990028_en_1.

D19 Food and Environmental Protection Act 1985. http://www.opsi.gov.uk/RevisedStatutes/Acts/ukpga/1985/cukpga_19850048_en_3.

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D21 Intervention for Recovery after Accidents. Doc NRPB 1997; 8, no.1, 1-20.

D22 UK Recovery Handbook for Radiation Incidents 2008, Version 2, Health Protection Agency, June 2008, ISBN 978-0-85951-622-8.

D23 NRPB (1990). Emergency Reference Levels of Dose for Early Countermeasures to Protect the Public. Doc NRPB, 1 (4), 5-33.

D24 NRPB (1997a). Application of Emergency Reference Levels of Dose in Emergency Planning and Response. Doc NRPB, 8 (1), 21-34.

D25 NRPB (1997b). Intervention for Recovery after Accidents. Doc NRPB, 8 (1), 1-20.

D26 ICRP (2007). The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103.

D27 ICRP (2008). Application of the Commission's Recommendations for the Protection of People in Emergency Exposure Situations. ICRP Publication 109.

D28 ICRP (2009). Application of the Commission's Recommendations for the Protection of People living in Long-term Contaminated Areas after a Nuclear Accident or a Radiation Emergency. ICRP Publication 111.

ANNEX E: ONR INVOLVEMENT IN THE CONVENTION ON NUCLEAR SAFETY

The United Kingdom (UK) was an active participant in the diplomatic meetings leading up to the development of the International Convention on Nuclear Safety (“the Convention”). In 1995 the UK ratified the Convention, becoming one of the original contracting parties when it came into force on 24 October 1996. The first Peer Review meeting under the terms of the Convention was held in Vienna in April 1999.

Article 5 of the Convention states “Each Contracting Party shall submit for review, prior to each meeting referred to in Article 20, a report on the measures it has taken to implement each of the obligations of this Convention” and Article 20 states “The Contracting Parties shall hold meetings (hereinafter referred to as "review meetings") for the purpose of reviewing the reports submitted pursuant to Article 5 in accordance with the procedures adopted under Article 22.” Article 21 further states “At each review meeting, the Contracting Parties shall determine the date for the next such meeting. The interval between review meetings shall not exceed three years.”

Since 1999, in compliance with the Articles, the UK has submitted reports to four further review meetings in 2002, 2005 and 2008, and at the last meeting in April 2011. Although the UK lead Government department is the Department of Energy and Climate Change (DECC) the bulk of the work related to this Convention has traditionally fallen to HSE/ONR as the regulatory body most closely associated with the intent of the Convention.

HSE/ONR has been active between the review meetings, not only in providing the UK national report and peer reviewing other national reports, but also in developing the quality and standards of the national reports by participating in working groups to enhance the report guidelines - with a view to the continuous improvement of nuclear safety worldwide.

ANNEX F: FLOOD RISKS AROUND NUCLEAR LICENSED SITES IN THE UK

Introduction

This annex contains information provided by the environment agencies (the Environment Agency in England and Wales and the Scottish Environment Protection Agency (SEPA) in Scotland) that was requested by the HM Chief Inspector about flood risks around UK nuclear sites, and consideration of UK tsunami risks in the light of the events in Japan.

The purpose of this annex is to:

- Provide an interim view on whether the recent events in Japan change our understanding of the risks and hazards from tsunamis around the UK coastline.
- Provide a strategic level summary of flood risks, including the effects of climate and coastal changes, around nuclear sites.
- Highlight some areas for further work.

Tsunami Risk and Hazard in the UK

The devastating tsunami in the Indian Ocean of December 2004 prompted the commissioning of a study by Department for Environment, Food and Rural Affairs (Defra) in 2005 into the threat posed by tsunami to the UK. To address specific questions raised in that report, Defra commissioned a further study in 2006 "Tsunamis – Assessing the hazard for the UK and Irish coasts"[1].

The 2005 Defra study identified four potential tsunami source origins (North Sea, Celtic Sea, offshore of Lisbon and La Palma in the Canary Islands). The likelihood of the event, the probability of the tsunami reaching the UK and the height of the wave were estimated for a range of possible events that might generate a tsunami that could affect the UK.

Two of these source origins were reviewed in more detail in the follow-up report, the North Sea event and a Lisbon-type event, with their consequence compared to an assessment of hazard. The objectives of the 2006 study were to:

- Refine the potential impact envelope in South West England, South Wales, the Bristol Channel, southern and western Ireland from Lisbon-type events.
- Further consider the difference between tsunami-type events and storm surge waves in terms of coastal impact.
- Investigate typical impacts of near-coast events.

Both the 2005 and 2006 Defra reports conclude that water levels expected from tsunami in the UK are not expected to be greater than those experienced from a storm surge event; however there is also recognition that the waveforms and therefore the impacts from tsunami and from storm surge may be different. The 2006 report presented the results of a hazard assessment and concluded that the most exposed area of the UK is the Cornish coast for a Lisbon-type event. Modelling results for the Cornish coast show wave elevations are typically in the range of 1-2m, with localised amplification enhancing the elevations to about 4m. The maximum water levels resulting from the Defra studies are an order of magnitude lower than the

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[1] http://archive.defra.gov.uk/environment/flooding/risk/tsunami.htm.

heights of tsunamis recorded off the east coast of Japan where the recent event was the third major tsunami in little over a century[m].

From the information currently available about the events in Japan there is no reason to suggest that the Regulators' approach (as described in the Office for Nuclear Regulation (ONR) Safety Assessment Principles (SAP) and other relevant guidance) to assessing the risks and hazards from tsunamis in the UK needs to change fundamentally, and in general the conclusions from the Defra reports remain valid. Taking this into account the Environment Agency's view is that the strategic advice that they provided to DECC during its Strategic Siting Assessment process, that the nominated sites for new nuclear build could potentially be protected from flooding, remains valid. This advice reflects that site specific flood risk assessments will be required if development proposals come forward. The Environment Agency have, in their interim submission, suggested a review of tsunami risks and the measures in place (including warning systems) to protect existing nuclear sites, and those proposed for new sites, from such events and to consider combinations of events and impacts on the sites' critical infrastructure.

Effects of Climate Change

Government has recently published its policy on adapting infrastructure to climate change[n] in which it sets out its vision – "An infrastructure network that is resilient to today's natural hazards and prepared for the future changing climate". Climate change impacts on flood risk from all sources. For those nuclear sites and infrastructure on the coasts, the impacts from sea level rise and increased wave heights need to be considered over the remaining lifetime of the facilities. This includes operation, decommissioning and waste storage phases. Assessment of climate change impacts should take due account of the Defra *Supplementary Note to Operating Authorities – Climate Change Impacts*, October 2006[o] (Defra 2006), and also demonstrate how the site can be managed and made safe against the latest[p] credible maximum climate change scenario for the site.

The credible maximum scenario is a peer reviewed and robust worst case but plausible scenario for the site which should be considered for contingency planning purposes. A current example of the credible maximum approach for sea level rise and storm surge for the period to 2100 is provided by UKCP09, through the H++ scenario[q]. The 2006 Defra guidance is being revised (publication expected summer 2011) to take account of the latest (UKCP09) projections which include more information on uncertainty and the credible maximum approach.

A managed adaptive approach to flood and coastal erosion risk management in the face of extreme climate change (credible maximum) can be adopted if required in the assessment of, and planning for future flood and coastal erosion risks.

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[m] http://www.insu.cnrs.fr/co/terre-solide/catastrophes-et-risques/seismes/sendai/sismicite-historique

[n] Climate Resilient Infrastructure: ''Preparing for a Changing Climate'' Defra 2011, Cm8065

[o] http://archive.defra.gov.uk/environment/flooding/documents/policy/guidance/fcdpag/fcd3climate.pdf

[p] In recognition of the fact that climate change predictions are likely to change over time as better science becomes available.

[q] http://ukclimateprojections.defra.gov.uk/content/view/1805/690/

The credible maximum climate change scenario should be used:

- To sensitivity test the impacts that climate change is expected to have on the facility, including site operation, safety and associated flood and coastal risk management measures, to ensure future adaptation to this scenario is not precluded.
- To inform the periodic safety review to ensure a managed adaptive approach to operation and nuclear safety can be put in place as required.

Coastal Change

Coastal change formed part of the Environment Agency's advice to DECC for their Strategic Siting Assessments (SSA) for the Nuclear National Policy Statement. While the Environment Agency's comments about access were provided in relation to nominated sites for new build, co-location also makes them applicable to existing facilities.

A full list of coastal erosion comments made by the Environment Agency at the SSA stage in relation to nuclear new build are available at the link below under the headings old material/specialist advice:

http://webarchive.nationalarchives.gov.uk/20110302182042/https://www.energynpsconsultation.decc.gov.uk/nuclear/nominated_sites.

Flood Risk Assessments for Areas around Nuclear Licensed Sites

SEPA and the Environment Agency hold high level information as to the potential flood hazard posed to nuclear locations across England, Scotland and Wales from fluvial (river), coastal and surface water sources. This is sufficient to provide a first indication of those areas potentially susceptible to flooding but not sufficient to provide a detailed quantitative assessment of the potential risk to an individual location. This information can be used to give an indication of potential impacts on supporting infrastructure such as road access/egress (see below) or transmission lines etc.

The Environment Agency, in partnership with SEPA, holds recently updated information on coastal conditions (e.g. sea-levels, swells and surge characteristics) around the coast of England, Wales and Scotland. This information is available to operators under licence.

Access/Egress

The potential impacts on access to, and egress from, sites formed part of the Environment Agency consultation response to the Strategic Siting Assessment (SSA) for the new build sites, within the flood risk section. While the Environment Agency's comments about access were provided in relation to nominated sites for new build, co-location also makes them applicable to existing facilities.

A full list of access comments made by the Environment Agency at the SSA stage in relation to nuclear new build are available to view at the link below, under the headings old material/specialist advice: http://webarchive.nationalarchives.gov.uk/20110302182042/https://www.energynpsconsultation.decc.gov.uk/nuclear/nominated_sites.

Of the nominated sites, the Environment Agency raised access and egress as a consideration for Dungeness, Hartlepool, Heysham, Oldbury and Sizewell.

Summary and Recommendation

Strategic level flood risk information can be derived from existing data held by the Environment Agency and SEPA. It indicates the potential for flooding to occur in the near vicinity of nuclear sites, but does not describe the specific *risk* to a facility because the detailed specific likelihood and consequences of flooding have not been assessed. Detailed site specific flood risk assessment can be carried out but these would require detailed knowledge of the site and of the risk management and operational arrangements that it has implemented and would take into account the potential impacts of climate change over the remaining lifetime of the site.

ONR requires licensees to take into account external hazards, including natural hazards such as flooding, within their safety cases and to review these safety cases on a regular basis. The Environment Agency and SEPA have recommended that they work with the Office for Nuclear Regulation to review whether there is a need to improve further the integration of site-specific flood risk assessments for areas on and off-site as part of the periodic safety review programme.

ANNEX G: SUMMARY OF SEISMIC AND FLOOD LEVELS FOR UK REACTOR SITES

Station	10^{-4} pa Seismic Hazard pga (g)	10^{-4} pa Flood Height (AOD) (m)	Flood Defence Heights (AOD) (m)
Dungeness B	0.21	5.4 (4) 8.7 (7)	8.0 (1)
Hunterston B	0.14	4.2 (8)	4
Hinkley Point B	0.14	5.9 (6) 10.4 (7)	8.8 (Sea wall) 12.0 (Gabion wall atop sea wall) (2)
Hartlepool	0.18	4.3 (6)	7.0 (Dunes) 5.7 (Sea wall) (3)
Heysham 1	0.23	7.6 (4)	10.7
Heysham 2	0.23	7.6 (4)	9.8
Sizewell B	0.14	7.6 (4)	10.0
Torness	0.13	3.5 (4)	9.0 (5)
Oldbury	0.16	9.2	10.2
Wylfa	0.18	9.4	12

Notes:

(1) *The flood protection is via an actively managed shingle berm*

(2) *The sea wall provides protection against static water levels. The Gabion wall provides protection against transient waves entering the site. A collector drain at the rear prevents water which passes through from progressing onto the site.*

(3) *The dunes directly face the sea, whereas the sea wall faces the harbour side and is more sheltered.*

(4) *Still water +Storm Surge + Wave. Tsunami effects minimal*

(5) *Platform level of Reactor building at +11.5m AOD*

(6) *Maximum still water level*

(7) *Maximum still water level + tsunami (conservative value). Limited overtopping is possible; however the tsunami levels used predate the latest DEFRA study work and are seen as very conservative.*

(8) *There is a potential for flooding of the CW pumphouse, however the bulk of the site is at a much higher elevation (Reactor building ground floor at +7.6m AOD)*

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GLOSSARY

Cliff-edge	A cliff-edge effect is a small change in a parameter that leads to a disproportionate increase in consequences.
Cold shutdown	The plant state where the core is subcritical, residual heat removal is established on a long-term basis, and radioactive discharges remain acceptable.
Epicentre	The epicentre is the point on the Earth's surface that is directly above the hypocenter or focus, the point where an earthquake or underground explosion originates.
Liquefaction	A phenomenon wherein a mass of soil loses a large percentage of its shear resistance when subjected to cyclic loading and flows in a manner resembling a liquid. This is typically a result of increased pore water pressure during undrained cyclic shear of saturated soils.
Magnitude	The earthquake magnitudes referred to in this report are M_w, Moment Magnitude.
M_L	Local Magnitude.
S_d	The seismic demand at the facility which requires the systems structures and components to maintain their safety functions as defined in JEAG 4601 (Ref. 27).
S_S	The seismic demand at the facility which requires the systems structures and components to maintain their safety functions as defined in JEAG 4601 (Ref. 27).

ABBREVIATIONS

AC	Alternating Current
ACR	Atriculated Control Rods
ADS	Automatic Depressurisation System
AEC	Atomic Energy Commission (Japan)
AGR	Advanced Gas-cooled Reactor
AIC	Alternative Indication Centre
ALARP	As Low As Reasonably Practicable
AOD	Above Ordnance Datum
AREVA	AREVA NP SAS
ASN	Autorité de Sûreté Nucléaire (French nuclear safety authority)
BWR	Boling Water Reactor
C&I	Control and Instrumentation
CAD	Containment Atmosphere Dilution
CFIL	Council Food Intervention Level
CNS	Convention on Nuclear Safety
COBR	Cabinet Office Briefing Room
CSF	Critical Safety Function
DBA	Design Basis Analysis
DC	Direct Current
DECC	Department of Energy and Climate Change
Defra	Department for Environment, Food and Rural Affairs
DEPZ	Detailed Emergency Planning Zone
DfT	Department for Transport
DG	Diesel Generator
DoH	Department of Health
ECC	Emergency Control Centre
EDF	EDF SA
EOP	Emergency Operating Procedures
ERL	Emergency Reference Level
FCO	Foreign and Commonwealth Office
FSA	Food Standards Agency
GDA	Generic Design Assessment
HPA	Health Protection Agency
HPA-CRCE	Health Protection Agency Centre for Radiation Chemical and Environmental Hazards

ABBREVIATIONS

	(formerly the NRPB)
HPCI	High Pressure Coolant Injection
HSE	Health and Safety Executive
HSWA	Health and Safety at Work etc. Act 1974
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IRRS	International Regulatory Review Service
LC	Licence Condition
LOCA	Loss of Coolant Accident
LOOP	Loss of Off-site Power
LPCI	Low Pressure Coolant Injection
LWR	Light Water Reactor
MDEP	Multi-national Design Evaluation Programme
METI	Ministry of Economy Trade and Industry (Japan)
MEXT	Ministry of Education Culture Sport Science and Technology (Japan)
MOX	Mixed Oxide Fuel
NEPLG	Nuclear Emergency Planning Liaison Group
NIA65	Nuclear Installations Act 1965
NEA	Nuclear Energy Agency (of the OECD)
NISA	Nuclear and Industrial Safety Agency (Japanese nuclear safety regulator)
NPP	Nuclear Power Plant
NSC	Nuclear Safety Commission
NRPB	National Radiological Protection Board (now HPA-CRCE)
OECD	Organisation for Economic Co-operation and Development
ONR	Office for Nuclear Regulation (formerly the Nuclear Directorate of the HSE)
OSP	Operational Safety Program
pga	Peek Horizontal Ground Acceleration
POSRV	Pilot Operated Safety Relief Valve
PSA	Probabilistic Safety Analysis
PSR	Periodic Safety Review
PWR	Pressurised Water Reactor
RCIC	Reactor Core Isolation Cooling
RCCA	Rod Cluster Control Assemblies
RCS	Reactor Coolant System

ABBREVIATIONS

REPPIR	Radiation (Emergency Preparedness and Public Information) Regulations 2001
RHR	Residual Heat Removal
RPD	Radiological Protection Division (of the HPA)
RPV	Reactor Pressure Vessel
SBERG	System Based Emergency Response Guidelines
SAG	Severe Accident Guidelines
SAGE	Scientific Advisor Group for Emergencies
SAM	Severe Accident Management
SAMG	Severe Accident Management Guidelines
SAP	Safety Assessment Principle(s) (HSE)
SBO	Station Blackout
SCC	Strategic Coordinating Centre
SEPA	Scottish Environment Protection Agency
SOI	Station Operating Instruction(s)
SoS	Secretary of State
SNUPPS	Standardised Nuclear Unit Power Plant System
SRV	Safety Relief Valve
SSA	Strategic Siting Assessment
TAP	Technical Advisory Panel
TEPCO	The Tokyo Electric Power Company
US NRC	Nuclear regulatory Commission (United States of America)
WAG	Welsh Assembly Government
WANO	World Association of Nuclear Operators
WHO	World Health Organisation

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