



Office for
Nuclear Regulation

Japanese earthquake and tsunami: Implications for the UK nuclear industry

Final Report

**HM Chief Inspector of Nuclear Installations
September 2011**

Office for Nuclear Regulation

An agency of HSE

© Crown copyright 2011

ONR Report ONR-FR-REP-11-002 Revision 2

First published September 2011

You may reuse this information (excluding logos) free of charge in any format or medium, under the terms of the Open Government Licence. To view the licence visit www.nationalarchives.gov.uk/doc/open-government-licence/, write to the Information Policy Team, The National Archives, Kew, London TW9 4DU, or email psi@nationalarchives.gsi.gov.uk.

Some images and illustrations may not be owned by the Crown so cannot be reproduced without permission of the copyright owner. Enquiries should be sent to copyright@hse.gsi.gov.uk.

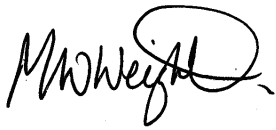
AP1000 is a registered trademark of Westinghouse Electric Company LLC in the United Kingdom and may be used or registered in other countries. Other names may be trademarks of their respective owners.

For published documents, the electronic copy on the ONR website remains the most current publically available version and copying or printing renders this document uncontrolled.

Acknowledgements

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.

A handwritten signature in black ink, appearing to read 'M Weightman', with a large, stylized flourish at the end.

Mike Weightman
HM Chief Inspector of Nuclear Installations
September 2011

Foreword

On 11 March 2011 Japan suffered its worst recorded earthquake. The epicentre was 110 miles east north east from the of the Fukushima Dai-ichi (Fukushima-1) nuclear power site which has 6 Boiling Water Reactors. Reactor Units 1, 2 and 3 on this site were operating at power before the event and on detection of the earthquake shut down safely. Initially 12 on-site back diesel generators were used to provide the alternating (AC) electrical supplies to power essential post-trip cooling. Within an hour a massive tsunami from the earthquake inundated the site. This resulted in the loss of all but one diesel generator, some direct current (DC) supplies and essential instrumentation, and created massive damage around the site. Despite the efforts of the operators eventually back-up cooling was lost. With the loss of cooling systems, Reactor Units 1 to 3 overheated. This resulted in several explosions and what is predicted to be melting of the fuel in the reactors leading to major releases of radioactivity, initially to air but later by leakage of contaminated water to sea.

It is clear that this was a serious nuclear accident, with an International Nuclear and Radiological Event Scale (INES) rating of Level 7 (the highest level). Tens of thousands of people were evacuated from a zone extending 20km from the site and remain so today. So far, the indications are that the public health effects from radiation exposure are not great.

The Secretary of State (SoS) for Energy and Climate Change requested on 14 March 2011 that I 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 by the middle of May 2011, which was published on 18 May 2011, and this final report within six months.

At the time of writing, not everything is known about the detailed circumstances and contributory factors, and may never be, given the state of the site after the tsunami. However, many facts are available, useful information has been submitted to us, more information has been gleaned from the International Atomic Energy Agency (IAEA) and other nation's regulatory activities, further analysis has been undertaken, and the Japanese Government has provided an extensive report. I also gained insights from my leading an international mission of experts to Japan, during which I visited the Fukushima Dai-ichi (Fukushima-1), Fukushima Dai-ni (Fukushima-2) and Tokai sites.

As indicated in my Interim Report, this Final Report is wider, covering all types of nuclear installations in the UK. Both reports 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 Organisation for Economic Co-operation and Development (OECD) and the IAEA.

As with the Interim Report, this Final Report does not examine nuclear policy issues. These are rightly matters for others 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 nuclear safety and its regulation in the UK.

From our work in bringing together this Final Report, having reviewed all the additional information and our further analysis, I am confident that the conclusion and recommendations of my Interim Report remain substantiated. Where appropriate, I have added to these with further clarification and some additional conclusions and recommendations.

A handwritten signature in black ink, appearing to read 'M Weightman', with a large, stylized loop at the end.

Mike Weightman
HM Chief Inspector of Nuclear Installations
September 2011

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 this 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 six months later. The Interim Report was published in May 2011.

This is the Final Report, referred to above. This report considers the implications for the UK nuclear industry, and has been expanded from focussing mainly on the nuclear power sector to cover all UK nuclear facilities.

This report provides some background on radioactive hazards, and how people are protected against them. It also provides background on nuclear power technology, and the approach to nuclear safety in the UK, internationally and in Japan. It also describes how we have taken forward the work and how we expect to report on final responses to our recommendations. The report details who we have liaised with and describes the measures we have put in place to provide independent technical advice for our work.

The detailed circumstances of the accident in Japan are not yet fully known and some may not be possible to determine given the loss of control and of certain instrumentation. Nevertheless, we consider that there is sufficient information to further develop lessons for the UK, and it is important to seek to draw early lessons wherever we can and to ensure those lessons are put into action in the UK as soon as possible. Sufficient was known by the time our Interim Report was finalised to enable us to draw key conclusions and recommendations.

Additional information has become available since our Interim Report; in particular, the report of the International Atomic Energy Agency (IAEA) fact-finding mission to Japan, and a large body of information in a report by the Japanese government. We have reviewed all of this information, and that of the many submissions to us, as well as conducting our own further analysis. This has enabled us to review our Interim Report recommendations and conclusions and undertake a review of the UK regulatory regime and our standards. As a result we have clarified and supplemented our Interim Report recommendations and made some new recommendations and conclusions. We have also set out our approach for taking the work forward.

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” (SFAIRP), which for assessment purposes is termed “as low as reasonably practicable” (ALARP). 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 the safety and security of their designs and operations to ensure their 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 nuclear facility designs and operations. However we are clear that if, in the light of information on the Fukushima accident, we were to become dissatisfied with the on-going safety of any existing nuclear facilities we would not hesitate to take appropriate action.

We believe that the significant lessons have been identified. However, with additional detailed information and research some extra detailed insights may be expected to 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 14:46 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 very large tsunami that inundated the Fukushima-1 site. The tsunami caused considerable damage and loss of life across Japan. There are several nuclear power sites in this area of Japan, in addition to 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, in which normal (light) water serves both as the reactor coolant and neutron 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 and pumped back into the reactor. 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 traditional 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 basement of reinforced concrete.

Both Mark I and II containment models have suppression chambers containing large volumes of water. The function of these chambers is to control pressure increases by condensing steam if an event occurs in which large quantities of steam are released from the reactor. The suppression pools are often referred to as a "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.

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% of the used fuel on-site is stored in the common pond, 34% 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 more time for operators to respond to loss of cooling accidents. Under loss of cooling conditions, significant quantities of hydrogen are not generated as water is not the primary coolant. Additionally, in conditions of overheating, the coolant it does not go through a phase change (liquid to gaseous state).

Sizewell B, which is the most recent nuclear power plant to be built in the UK, is a PWR that 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. It 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 Reactor 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 alternating current (AC) electrical power to the cooling systems for the reactor and reactor fuel ponds was lost, including that from backup diesel generators (although one remained able to operate for Reactor Unit 6 and then Reactor Unit 5). Over the next few days, the fuel heated up and its cladding reacted with steam releasing hydrogen, which ignited, causing several large explosions. In addition, fuel element integrity was lost and containment was breached, 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. For over a week the site struggled to put cooling water into the reactors and the reactor fuel ponds, by using untried and unplanned means. 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.

It was clear that this was a serious nuclear accident. A provisional International Nuclear and Radiological 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 Level 7.

Early on in the chain of events the Japanese authorities instigated a 3km evacuation zone, and later a 20km zone with a 30km sheltering zone along with other countermeasures. Governments across the world watched with concern as they considered 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. We (the Health and Safety Executive's Nuclear Directorate, which became the Office for Nuclear Regulation (ONR) – an agency of the 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, we have taken action on a number of fronts. Firstly, a dedicated project team has been set up, including technical support to cover aspects of the Fukushima event likely to be important in learning lessons. The technical areas include: external hazards, radiological protection, reactor physics, severe accident analysis, probabilistic safety analysis, human factors, management of safety, civil engineering, electrical engineering, nuclear fuel, spent fuel storage and emergency arrangements.

Secondly, in addition to ONR's internal team, we have actively sought assistance from a wide range of organisations, issued a broad invitation to anyone able and willing to assist, and liaised with leading nuclear regulators and other bodies worldwide.

Thirdly, in order to provide independent technical advice to HM Chief Inspector of Nuclear Installations during the production of both the Interim and this Final 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 our Interim and Final Reports.

A number of authoritative reports have been published over the summer. These include a substantial report from the Japanese government to the IAEA Ministerial Conference; the report of an IAEA fact-finding mission to Japan; and the report of the US Nuclear Regulatory Commission's (US NRC) near-term task force review of insights from the Fukushima accident. We recognise the importance of learning from others and have reviewed each of these documents. We have used them also in our consideration of the many submissions we have received, in undertaking further analysis, and in reviewing the conclusions and recommendations of our Interim Report. They have proved very helpful in clarifying our understanding of the accident progression and have provided insights into safety and emergency preparedness issues for the UK in a number of areas.

Conclusions

In this Final Report, we have derived various conclusions through consideration of the further information and analysis since our Interim Report. These fall into two categories: those related to our consideration of the UK nuclear safety philosophy and regulatory regime reflecting on the circumstances and known facts of the Fukushima accident; and those relating to our review of the information in relation to our Interim Report conclusions. These are summarised below.

UK Nuclear Safety Philosophy and Regulatory Regime

Whenever a major accident occurs there are, not unreasonably, questions and comments directed to the regulatory body in relation to its role in overseeing the safety of the affected facilities. Often questions arise over the independence of the regulator, its approach and standards and the effective use of its powers. The structure, responsibilities and role of the Japanese regulatory body were reviewed in 2007 by IAEA, with recommendations and suggestions for some improvements being made. There have been some reports in the media in relation to the Japanese regulator's role and approach, and the adverse bearing this may have had on events at Fukushima. The IAEA fact-finding mission made further observations on the Japanese regulatory system. Additionally, the Japanese official investigation committee will include in its review the role of the regulator. However, the Japanese government has already indicated that significant organisational changes are to come, with a view to creating a more independent and effective regulatory body.

No similar concerns have been identified in relation to the UK's nuclear regulator; here it operates independently both of the industry and of Government, which is important given the Government's policy of promoting nuclear power. In addition, it is the Government's intention to create a more integrated, focused, independent and accountable nuclear regulatory body with the greater institutional flexibility necessary to sustain the high level of expertise within it to meet the challenges of the future. Renaming the Nuclear Directorate as ONR and establishing it as an agency of HSE on 1 April 2011 was an interim step. Ultimately, ONR is to become a standalone statutory corporation outside of HSE. IAEA endorsed these plans in its second Integrated Regulatory Review Service (IRRS) peer review mission to the UK in 2009; the then Deputy Director General of IAEA praised the steps being taken to create an autonomous, more independent, well resourced nuclear regulator.

The direct causes of the nuclear accident at Fukushima, a magnitude 9 earthquake and the associated 14m high tsunami, are far beyond the most extreme natural events that the UK would be expected to experience. Design provisions at the Fukushima-1 site were only recently made to protect against a 5.7m high surge in sea level. The IAEA fact-finding mission remarked on the inadequacies of the design basis for tsunamis. Further, in their report to IAEA, the Japanese government openly acknowledges that the design for tsunami was inadequate and that there were deficiencies in the design basis for tsunamis. Our approach differs from the Japanese as we use a goal-setting approach rather than a purely deterministic, prescriptive, methodology. It is clear that in the development of its Safety Assessment Principles (SAP), ONR Inspectors anticipated potential combinations of events, such as those that occurred at Fukushima-1, and the UK consequently has a robust, structured and comprehensive methodology for identifying design basis events.

Conclusion FR-1: Consideration of the accident at Fukushima-1 against the ONR Safety Assessment Principles for design basis fault analysis and internal and external hazards has shown that the UK approach to identifying the design basis for nuclear facilities is sound for such initiating events.

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.

One of the key parts of the UK nuclear safety regime is that of Periodic Safety Review (PSR). ONR and its predecessors have for some decades required nuclear site licensees to perform PSRs at least every 10 years. This aligns with IAEA safety standards and guides and in the UK is a legal requirement enforced through nuclear site Licence Condition 15. These PSRs are thoroughly assessed by ONR and substantial plant modifications have been made as a result of the PSRs.

The requirement to perform PSRs applies equally to nuclear fuel cycle and decommissioning facilities. In some facilities that are no longer operational, but are still storing nuclear materials prior to their complete decommissioning, it is neither reasonably practicable nor possible in some cases to close the gap with modern standards sufficiently, or possible to call an immediate halt to storage. The Sellafield legacy fuel storage ponds and intermediate level waste storage silos are the prime examples of such facilities. The licensee, the Nuclear Decommissioning Authority (which owns the site) and Government, all regard urgent progress with the legacy ponds and silos remediation and retrievals programme as a national priority. This priority is reinforced by the example of the Fukushima accident where the vulnerabilities of older plant were not sufficiently recognised and addressed.

Conclusion FR-2: The Fukushima accident reinforces the need for the Government, the Nuclear Decommissioning Authority and the Sellafield Licensee to continue to pursue the Legacy Ponds and Silos remediation and retrievals programme with utmost vigour and determination.

By way of contrast, the report by the Japanese government states that PSRs were carried out by Japanese licensees on a voluntary basis and although some aspects of these were made mandatory in 2003, the provision of a PSA to assess the overall risks presented by the sites remained voluntary and the regulator ceased performing reviews.

Conclusion FR-3: The mandatory requirement for UK nuclear site licensees to perform periodic reviews of their safety cases and submit them to ONR to permit continued operation provides a robust means of ensuring that operational facilities are adequately improved in line with advances in technology and standards, or otherwise shut down or decommissioned.

In order to appreciate the environmental conditions that could arise in severe accidents and identify any reasonably practicable measures that might be taken to mitigate their consequences, it is necessary to understand the physical and chemical phenomena that could occur, the circumstances under which they might, and their likelihoods.

* The prefix "FR" has been used to distinguish conclusions made in the Final Report from those made in the Interim Report.

The information needed to address our severe accident SAPs requires a Probabilistic Safety Analysis (PSA) to at least Level 2 to enable analysts to understand the risk profiles of different plant and identify any vulnerabilities that might be reduced by implementing improvements to the design or operation, including severe accident management. Level 2 PSAs combine analyses of the probabilities of different potential accident sequences with an understanding of severe accident progression and the barriers to fission product release in order to provide information on the frequencies and characteristics of different fission product releases to the environment. A Level 3 PSA would provide additional information on offsite effects, but this could not be used by the licensee to enhance on-site accident mitigation measures. We consequently conclude that:

Conclusion FR-4: The circumstances of the Fukushima accident have heightened the importance of Level 2 Probabilistic Safety Analysis for all nuclear facilities that could have accidents with significant off-site consequences.

Conclusions from the Interim Report

The conclusions from the Interim Report are listed in full below, noting that they continue to stand.

Conclusion IR-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.

Conclusion IR-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.

Conclusion IR-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.

Conclusion IR-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.

Conclusion IR-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.

[†] The prefix "IR" has been used to identify clearly those conclusions from the Interim Report. Conclusion IR-1 here is therefore the same as Conclusion 1 in the Interim Report.

Conclusion IR-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.

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

Conclusion IR-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 given adequate demonstration in design and operational safety cases.

Conclusion IR-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.

Conclusion IR-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.

Conclusion IR-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.

The additional information available about the accident since the publication of the Interim Report, supplemented by various submissions and our own further analysis, has reinforced, and added further substance to, the Interim Report conclusions and recommendations. We therefore conclude that our Interim Report conclusions remain valid, viz:

Conclusion FR-5: The additional information we have received since our Interim Report, and our more detailed analysis, has added further substantiation to, and reinforced, our initial conclusions and recommendations.

Furthermore, there have been positive responses from Government, industry and regulators to the Interim Report and we have been satisfied with the programmes of work initiated so far. This is in line with a national commitment to a positive safety culture. We conclude therefore:

Conclusion FR-6: The Industry and others have responded constructively and responsibly to the recommendations made in our interim report and instigated, where necessary, significant programmes of work. This shows an on-going commitment to the principle of continuous improvement and the maintenance of a strong safety culture.

Recommendations

As a result of our consideration of the events at the Fukushima-1 site, the Interim Report identified various matters that we considered should be reviewed to determine whether there are any reasonably practicable improvements to the safety of the UK nuclear industry. We also identified some more general matters for consideration. Since publication of the Interim Report we have carried out further work and held discussions with many stakeholders, and have identified a number of areas where we consider it beneficial to elaborate or clarify the recommendations made there. In addition, we have identified some new recommendations and these are all included in the tables below.

As with the Interim Report, we have grouped the recommendations into logical categories and to identify those we expect to follow up the recommendations. The recommendations are listed in full below with the Interim Report and Final Report recommendations identified differently noting that the Interim Report ones continue to stand.[‡]

General	
International Arrangements for Response	<p>Recommendation IR-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.</p> <p><i>This information should include:</i></p> <ul style="list-style-type: none"> a) <i>basic data about the reactor design including reactor type, containment, thermal power, protection systems, operating history and condition of any nuclear materials such as spent fuel stored on the site should be held permanently in a central library maintained on behalf of the international community; and</i> b) <i>data on accident progression and the prognosis for future accident development. The operator would provide such information as is available to its national authorities. International mechanisms for communicating this information between national governments should be strengthened. To ensure that priority is given to relevant information, international agreement should be sought on the type of information that needs to be provided.</i>
Global Nuclear Safety	<p>Recommendation FR-9: The UK Government, nuclear industry and ONR should support international efforts to improve the process of review and implementation of IAEA and other relevant nuclear safety standards and initiatives in the light of the Fukushima-1 (Fukushima Dai-ichi) accident.</p>

[‡] It should be noted that the Final Report recommendations identification in these lists are not sequential as they follow the sequence of where they are derived in the “Discussion” Section. Furthermore, “IR” refers to “Interim Report” and not interim recommendation – they are all still valid. Italics identify where additional clarification is provided.

General	
National Emergency Response Arrangements	<p>Recommendation IR-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.</p> <p>Recommendation IR-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.</p> <p><i>This information should include the practicability and effectiveness of the arrangements for extending countermeasures beyond the Detailed Emergency Planning Zone (DEPZ) in the event of more serious accidents.</i></p> <p>Recommendation FR-6: The nuclear industry with others should review available techniques for estimating radioactive source terms and undertake research to test the practicability of providing real-time information on the basic characteristics of radioactive releases to the environment to the responsible off-site authorities, taking account of the range of conditions that may exist on and off the site.</p> <p>Recommendation FR-7: The Government should review the adequacy of arrangements for environmental dose measurements and for predicting dispersion and public doses and environmental impacts, and to ensure that adequate up to date information is available to support decisions on emergency countermeasures.</p>
Planning Controls	<p>Recommendation FR-5: The relevant Government departments in England, Wales and Scotland should examine the adequacy of the existing system of planning controls for commercial and residential developments off the nuclear licensed site.</p>
Openness and Transparency	<p>Recommendation IR-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.</p> <p>Recommendation FR-8: The Government should consider ensuring that the legislation for the new statutory body requires ONR to be open and transparent about its decision-making, so that it may clearly demonstrate to stakeholders its effective independence from bodies or organisations concerned with the promotion or utilisation of nuclear energy.</p>

Relevant to the Regulator	
Safety Assessment Approach	<p>Recommendation IR-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.</p> <p><i>The review of ONR's Safety Assessment Principles (SAP should also cover ONR's Technical Assessment Guides (TAG), including external hazards.</i></p>

Relevant to the Regulator	
Emergency Response Arrangements and Exercises	<p>Recommendation IR-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.</p> <p><i>This should include:</i></p> <ul style="list-style-type: none"> a) <i>evaluation of how changes to exercise scenarios supported by longer exercise duration will permit exercising in real time such matters as hand-over arrangements, etc.;</i> b) <i>how automatic decisions taken to protect the public can be confirmed and supported by plant damage control data; and</i> c) <i>recommendations on what should be included in an appropriate UK exercise programme for testing nuclear emergency plans, with relevant guidance provided to Radiation (Emergency Preparedness and Public Information) Regulations 2001 (REPPiR) duty holders.</i> <p>Recommendation IR-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.</p> <p><i>This should include:</i></p> <ul style="list-style-type: none"> a) <i>enhancing access during an accident to relevant, current plant data on the status of critical safety functions, i.e. the control of criticality, cooling and containment, and releases of radioactivity to the environment, as it would greatly improve ONR's capability to provide independent advice to the authorities in the event of a severe accident; and</i> b) <i>review of the basic plant data needed by ONR – this has much in common with what we suggest should be held by an international organisation under Recommendation IR-1.</i>
Research	<p>Recommendation FR-10: ONR should expand its oversight of nuclear safety-related research to provide a strategic oversight of its availability in the UK as well as the availability of national expertise, in particular that needed to take forward lessons from Fukushima. Part of this will be to ensure that ONR has access to sufficient relevant expertise to fulfil its duties in relation to a major incident anywhere in the world.</p>

Relevant to the Nuclear Industry	
Off-site Infrastructure Resilience	<p>Recommendation IR-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.</p> <p><i>This should include:</i></p> <ul style="list-style-type: none"> a) essential supplies such as food, water, conventional fuels, compressed gases and staff, as well as the safe off-site storage of any equipment that may be needed to support the site response to an accident; and b) timescales required to transfer supplies or equipment to site. <p>Recommendation IR-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.</p>
Impact of Natural Hazards	<p>Recommendation IR-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.</p>
Multi-reactor Sites	<p>Recommendation IR-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.</p>
Spent Fuel Strategies	<p>Recommendation IR-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.</p> <p><i>Existing licensees are expected to review their current spent fuel strategies as part of their periodic review processes and make any reasonably practicable improvements, noting that any intended changes need to take account of wider strategic factors including the implications for the nuclear fuel cycle.</i></p>
Site and Plant Layout	<p>Recommendation IR-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.</p> <p><i>This recommendation is related to Recommendation IR-25 and should be considered along with the provisions put in place under that recommendation. It should include, for example, the operator's capability to undertake repairs and the availability of spare parts and components.</i></p>

Relevant to the Nuclear Industry	
Fuel Pond Design	<p>Recommendation IR-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.</p>
Seismic Resilience	<p>Recommendation IR-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.</p> <p><i>The industry focus on this recommendation should be on future studies regarding the continuing validation of methodologies for analysing the seismic performance of structures, systems and components important to safety. This should include concrete structures and those fabricated from other materials.</i></p>
Extreme External Events	<p>Recommendation IR-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.</p> <p>Recommendation FR-2: The UK nuclear industry should ensure that structures, systems and components needed for managing and controlling actions in response to an accident, including plant control rooms, on-site emergency control centres and off-site emergency centres, are adequately protected against hazards that could affect several simultaneously.</p> <p>Recommendation FR-3: Structures, systems and components needed for managing and controlling actions in response to an accident, including plant control rooms, on-site emergency control centres and off-site emergency centres, should be capable of operating adequately in the conditions, and for the duration, for which they could be needed, including possible severe accident conditions.</p>
Off-site Electricity Supplies	<p>Recommendation IR-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.</p>
On-site Electricity Supplies	<p>Recommendation IR-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.</p> <p><i>This should be considered along with Recommendation IR-8 within the wider context of “on-site resilience”.</i></p>
Cooling Supplies	<p>Recommendation IR-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.</p> <p>Recommendation IR-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.</p>

Relevant to the Nuclear Industry	
Combustible Gases	<p>Recommendation IR-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.</p>
Emergency Control Centres, Instrumentation and Communications	<p>Recommendation IR-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.</p> <p><i>In particular, the review should consider that the Fukushima-1 site was equipped with a seismically robust building housing the site emergency response centre which had: adequate provisions to ensure its habitability in the event of a radiological release; and communication facilities with on-site plant control rooms and external agencies, such as TEPCO headquarters in Tokyo.</i></p> <p>Recommendation IR-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.</p> <p><i>In addition to impacting communications, it is possible that external events could also affect off-site centres used to support at site in an emergency. Alternative locations should be available and they should be capable of being commissioned in an appropriate timescale.</i></p>

Relevant to the Nuclear Industry

Human Capabilities and Capacities

Recommendation IR-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.

This is a wide ranging recommendation and there are a number of aspects that need to be included:

- a) the reviews need to acknowledge design differences between individual nuclear facilities and consider whether corporate Severe Accident Guidelines need to be customised;*
- b) adequacy of trained personnel numbers for long-term emergencies, particularly for multi-unit sites, and taking into account the potential impact of infrastructure damage and societal issues on the ability to mobilise large numbers of personnel;*
- c) the time windows for availability of off-site support may be challenged hence the role of on-site personnel may change, which has implications for procedures and training;*
- d) the review of Severe Accident Management Guidelines (SAMG) should consider not only critical safety functions prioritisation, but also whether and how SAMGs support any dynamic reprioritisation based on emerging information;*
- e) consideration should also be given to operator support requirements relating to tactical and strategic decision making; and*
- f) in addition to the acute phase of a severe accident, consideration also needs to be given to stabilisation, recovery and clean-up, and the personnel involved from the many organisations involved.*

Recommendation FR-11: The UK nuclear industry should continue to promote sustained high levels of safety culture amongst all its employees, making use of the National Skills Academy for Nuclear and other schemes that promote “nuclear professionalism”.

Relevant to the Nuclear Industry

Safety Case

Recommendation IR-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.

Recommendation IR-25 is linked with Recommendation IR-13. Combining these two recommendations means that we would expect industry to:

- a) identify potential strategies and contingency measures for dealing with situations in which the main lines of defence are lost. Considerations might include, for example, the operator’s capability to undertake repairs and the availability of spares (capability includes the availability of personnel trained in the use of emergency equipment along with necessary supporting resources);*
- b) consider the optimum location for emergency equipment, so as to limit the likelihood of it being damaged by any external event or the effects of a severe nuclear accident;*
- c) consider the impact of potential initiating events on the utilisation of such equipment;*
- d) consider the need for remotely controlled equipment including valves;and*
- e) consider in the layout of the site effective segregation and bunding of areas where radioactive liquors from accident management may accumulate.*

Regarding other aspects of Recommendation IR-25, the industry needs to:

- f) ensure it has the capability to analyse severe accidents to properly inform and support on-site severe accident management actions and off-site emergency planning. Further research and modelling development may be required;*
- g) ensure that sufficient severe accident analysis has been performed for all facilities with the potential for accidents with significant off-site consequences, in order to identify severe accident management and contingency measures. Such measures must be implemented where reasonably practicable and staff trained in their use; and*
- h) examine how the continued availability of sufficient on-site personnel can be ensured in severe accident situations, as well as considering how account can be taken of acute and chronic stress at both an individual and team level (this is linked to Recommendation IR-24).*

Recommendation FR-1: All nuclear site licensees should give appropriate and consistent priority to completing Periodic Safety Reviews (PSR) to the required standards and timescales, and to implementing identified reasonably practicable plant improvements.

Recommendation FR-4: The nuclear industry should ensure that adequate Level 2 Probabilistic Safety Analyses (PSA) are provided for all nuclear facilities that could have accidents with significant off-site consequences and use the results to inform further consideration of severe accident management measures. The PSAs should consider a full range of external events including “beyond design basis” events and extended mission times.

Way Forward	
Way forward	<p>Recommendation IR-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.</p> <p><i>This recommendation was met in full by all of those on whom the recommendations fell, and is therefore discharged.</i></p> <p>Recommendation FR-12: Reports on the progress that has been made in responding to the recommendations in this report should be made available to ONR by June 2012. These should include the status of the plans, together with details of improvements that have been implemented by that time.</p>

Way Forward

In response to a request from the Council of the European Union, a specification for “Stress Tests” for nuclear power stations has been developed and we have required the licensees to undertake this work. Licensees’ efforts to complete the stress tests are well underway and, once completed, we will assess them and require any necessary improvements in line with the ALARP principle. We will also produce a UK National Report to the European Council. We are currently engaged with our European partners in developing an appropriate peer review process for the “Stress Tests” to enable learning to be shared across all of the countries involved.

There are overlaps between the “Stress Tests” outcomes and the recommendations in our reports. Hence the nuclear industry will, no doubt, produce a common plan for responding to the “Stress Tests” as well as the recommendations in this report. In line with our drive for greater openness and transparency, we expect this plan to be published.

The outcome of work to meet our recommendations and the outcomes from 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” and the full response to our recommendations, we have decided to produce a further report in about a year’s time which will provide an update on progress in implementing the lessons for the UK’s nuclear industry.

Contents

INTRODUCTION	1
Aims of the Report.....	1
Scope	2
Relevant Additional UK Responses	2
BACKGROUND	4
General Background	4
<i>Hazards, Hazard Potential, Barriers and Risks</i>	4
<i>Radiation, Radioactivity and Risk to Humans from Exposure</i>	5
<i>Protection Against Radiation</i>	6
<i>Nuclear Power Stations</i>	6
<i>Safety of Nuclear Power Reactors</i>	7
<i>Design Basis Analysis</i>	8
<i>Probabilistic Safety Analysis and Severe Accidents</i>	8
Japanese Nuclear Power Industry	9
Japanese Nuclear Regulatory Regime	10
<i>Nuclear Safety Commission</i>	11
<i>Nuclear and Industrial Safety Agency</i>	11
<i>Commentary on Japanese Regulatory Body</i>	11
Technology Used at the Fukushima-1 Site	13
<i>BWR Cooling Cycle</i>	13
<i>Reactor</i>	14
<i>Containment</i>	16
Spent Fuel Storage.....	19
UK NUCLEAR INDUSTRY.....	20
UK Nuclear Power Industry.....	20
UK Non-nuclear Power Plant Nuclear Facilities.....	21
<i>Sellafield</i>	21
<i>Dounreay</i>	22
<i>Winfrith</i>	22
<i>Harwell</i>	22
<i>Springfields</i>	22
<i>URENCO UK</i>	23
<i>Capenhurst (Sellafield Limited)</i>	23
<i>Low Level Waste Repository</i>	23
<i>Metals Recycling Facility</i>	23
<i>Imperial College Consort Reactor</i>	23
<i>GE Healthcare Limited Sites</i>	23
<i>Defence Nuclear Licensed Sites</i>	23
<i>Defence Nuclear Non-licensed Sites</i>	24

UK NUCLEAR REGULATORY REGIME	25
<i>Legal Framework</i>	25
<i>Department of Energy and Climate Change</i>	25
<i>Office for Nuclear Regulation</i>	26
<i>Environment Agencies</i>	26
<i>Health Protection Agency</i>	26
<i>ONR Regulatory Approach</i>	27
UK NUCLEAR EMERGENCY ARRANGEMENTS	29
OVERVIEW OF THE FUKUSHIMA ACCIDENT AND KEY FACTORS	30
Summary	30
Timeline of Key Events	30
<i>Impacts of the Earthquake on the Site</i>	31
<i>Impact of the Tsunami on the Site</i>	31
<i>Broader Impact on Local Area Around the Site</i>	33
<i>Conditions at Fukushima-1 Prior to the Earthquake</i>	34
<i>Sequence of Events in Reactor Unit 1</i>	34
<i>Sequence of Events in Reactor Unit 2</i>	36
<i>Sequence of Events in Reactor Unit 3</i>	38
<i>Reactor Unit 1 to 4 Fuel Ponds</i>	40
<i>Reactor Units 5 and 6</i>	42
<i>Restoration of Off-site Power</i>	43
<i>Common Spent Fuel Pond</i>	44
<i>Dry Cask Storage Facility</i>	44
Role and Relevance of Key Reactor Systems During the Fukushima Accident	44
<i>Reactivity Control</i>	45
<i>Normal Post-trip Cooling</i>	45
<i>Reactor Pressure Control</i>	47
<i>Reactor Inventory Control and Emergency Core Cooling Systems</i>	48
<i>Containment Pressure and Temperature Control</i>	54
<i>Hydrogen Control</i>	58
Spent Fuel Pond Factors During the Fukushima Accident	58
Protection of Fukushima-1 Reactor Units against Natural Hazards and the Impact of the Events	61
<i>Seismic Design</i>	61
<i>Design Against Flooding</i>	62
<i>Factors Relating to the Local Grid System</i>	63
Key On-site Factors Relating to Electrical Systems	64
Key On-site Factors Relating to Control and Instrumentation Systems	64
Key On-site Factors Relating to Operator Actions	65
<i>Fukushima-1 Operator Actions</i>	66
<i>Reactor Unit 1</i>	66
<i>Reactor Unit 2</i>	67

<i>Reactor Unit 3</i>	68
<i>Reactor Units 5 and 6</i>	69
<i>Spent Fuel Ponds</i>	70
<i>Fukushima-2 Operator Actions</i>	71
MAIN ASPECTS RELEVANT TO THE UK.....	72
Protection of UK Nuclear Installations from Natural Hazards.....	72
<i>Overview</i>	72
<i>Regulatory Expectations</i>	72
<i>Seismic Hazards in the UK</i>	73
<i>Tsunami Hazards in the UK</i>	74
<i>Event Combinations</i>	74
Relevant Aspects of UK Reactor Technology.....	75
<i>Introduction</i>	75
<i>Reactivity Control</i>	77
<i>Post-trip Cooling</i>	78
<i>Containment</i>	79
<i>Severe Accident Management</i>	80
<i>UK Reactor Site Spent Fuel Storage</i>	82
Relevant Aspects of UK Non-reactor Technology.....	83
<i>Introduction</i>	83
<i>Sellafield</i>	83
<i>Commercial and Restoration Sites</i>	84
<i>Atomic Weapons Establishment, Aldermaston and Burghfield</i>	86
<i>Nuclear Fuel Production Plant and Neptune Reactor, Derby, Derbyshire</i>	86
<i>Devonshire Dock Complex, Barrow-in-Furness, Cumbria</i>	86
<i>Devonport Royal Dockyard, Plymouth</i>	86
<i>Rosyth Royal Dockyard</i>	87
HUMAN AND ORGANISATIONAL FACTORS.....	88
Human Factors.....	88
<i>Severe Accident Management Strategy in the UK</i>	88
<i>Implications for UK Power Reactor Facilities, Including New Nuclear Build</i>	88
<i>Availability of Personnel for Severe Accident Management</i>	89
<i>Technical / Procedural Support - Severe Accident Management Guidelines</i>	90
<i>Operator Training and Severe Accident Rehearsal</i>	90
<i>Availability of Control and Instrumentation, Including Communications and Equipment and Power Supplies</i>	91
Organisational Factors.....	91
<i>Doses to Intervention Personnel</i>	92
<i>Public Protection Countermeasure Zone</i>	93
<i>Distribution of Potassium Iodate Tablets</i>	93
<i>Monitoring, Decontamination and Medical Assistance of Evacuees, Casualties and Intervention Personnel</i>	94

<i>Radiological Monitoring of the Environment</i>	94
<i>Taking Agricultural Countermeasures, Countermeasures Against Ingestion and Longer Term Protective Actions</i>	94
Robustness of the UK Grid.....	95
Emergency Arrangements	96
RESPONSES TO INTERIM REPORT RECOMMENDATIONS	97
<i>Recommendations Relevant to the Government – Recommendation IR-1</i>	100
<i>Recommendations Relevant to the Government – Recommendation IR-2</i>	101
<i>Recommendations Relevant to NEPLG – Recommendation IR-3</i>	101
<i>Recommendations Relevant to the Regulator (ONR) – Recommendation IR-4</i>	103
<i>Recommendations Relevant to the Regulator (ONR) – Recommendation IR-5</i>	104
<i>Recommendations Relevant to the Regulator (ONR) – Recommendation IR-6</i>	105
<i>Recommendations Relevant to the Regulator (ONR) – Recommendation IR-7</i>	105
<i>Recommendations Relevant to the Nuclear Industry</i>	107
Progress on European Council “Stress Tests”	120
Other Stakeholder Submissions.....	121
EXTERNAL TECHNICAL ADVICE	122
Technical Advisory Panel	122
INTERNATIONAL ATOMIC ENERGY AGENCY MISSION TO JAPAN.....	124
Summary of Mission to Japan.....	124
Key Conclusions of the Mission	125
Lessons Learnt	126
Impact of the IAEA Mission’s Lessons and Conclusions on the UK Situation	127
LESSONS LEARNT IN THE REPORT OF THE JAPANESE GOVERNMENT TO THE INTERNATIONAL ATOMIC ENERGY AGENCY.....	128
DISCUSSION	129
Introduction	129
Reports from International Authorities.....	130
<i>IAEA Fact-finding Mission</i>	130
<i>Report of the Japanese Government</i>	131
<i>Report of the US NRC’s Near-term Task Force</i>	132
Stakeholder Submissions and Industry Responses.....	133
Consideration of Lessons for the UK Nuclear Safety System and Regulatory Regime	133
<i>Safety Philosophy</i>	133
<i>Safety Assessment Principles</i>	135
<i>Accident Prevention</i>	136
<i>Responding to Advances in Technology and Standards</i>	140
<i>Accident Mitigation</i>	142
<i>Public Protection</i>	144
<i>Research</i>	149
Interim Report Conclusions and Recommendations	149

<i>General</i>	149
<i>Specific Conclusions and Recommendations from the Interim Report</i>	151
<i>Fuel</i>	157
Stress Tests	158
ANNEX A: INTERNATIONAL CO-OPERATION	160
ANNEX B: HISTORICAL GENERAL RISKS ASSOCIATED WITH VARIOUS HAZARDS.....	161
ANNEX C: TYPICAL EXPOSURES TO IONISING RADIATION FROM DIFFERENT ACTIVITIES	164
ANNEX D: EMERGENCY ARRANGEMENTS IN THE UK	165
ANNEX E: ONR INVOLVEMENT IN THE CONVENTION ON NUCLEAR SAFETY	173
ANNEX F: FLOOD RISKS AROUND NUCLEAR LICENSED SITES IN THE UK.....	174
ANNEX G: SUMMARY OF FLOOD RISK TO EXISTING UK NUCLEAR INSTALLATIONS	180
ANNEX H: EUROPEAN COUNCIL STRESS TESTS	210
ANNEX I: IAEA JAPANESE MISSION - CONCLUSIONS AND LESSONS.....	222
ANNEX J: JAPANESE GOVERNMENT REPORT TO IAEA – LESSONS.....	227
ANNEX K: FUKUSHIMA-1 OPERATOR ACTION SUMMARY	252
ANNEX L: PROGRESSION OF THE SEVERE ACCIDENT AT FUKUSHIMA-1 REACTOR UNITS 1, 2 AND 3	264
REFERENCES	276
GLOSSARY AND ABBREVIATIONS.....	281
CONTACTS	288

INTRODUCTION

- 1 This Final Report builds on and adds to our work in the Interim Report (Ref. [1](#)), looking at the lessons for the UK nuclear industry that have been learnt from the accident that took place at the Fukushima-1 site in Japan. We have worked 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 This report is written so that it encompasses the Interim Report and can be read as a standalone document. However, we have not repeated all of the reasoning behind the Interim Report recommendations and readers may wish to refer to that report for specific information. The 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 and how we expect to report on progress on the recommendations. 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.
- 3 We intend to produce a supplementary report about a year from now to cover progress and close-out of the recommendations and the outcome of “Stress Tests” initiated by the European Council.

Aims of the Report

- 4 HM Chief Inspector of Nuclear Installations intends that the Final Report 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) permits;
 - 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; and
 - 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.
- 5 These are the same aims as those of the Interim Report.

Scope

- 6 In defining the scope of this report we have built on the foundations of the Interim Report and have enlarged a number of the sections taking account of information that was not available at that time. The main sources of this new information have been the report of the Japanese government to the International Atomic Energy Agency (IAEA) (Ref. [2](#)) and the report of the IAEA fact-finding expert mission to Japan (Ref. [3](#)), the latter being an example of co-operation at an international level on this topic.
- 7 We have also expanded the scope of this report to cover not only the UK's nuclear power plants, but all licensed nuclear installations in the UK.
- 8 As with the Interim Report, this Final Report does 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 HM Chief Inspector of Nuclear Installations.
- 9 The report 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

- 10 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.
- 11 The Government Chief Scientific Advisor, 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.
- 12 Our 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.
- 13 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 co-ordination centre, inviting key organisations in the multi-agency response - i.e. the Department for Environment, Food and Rural Affairs (Defra), the Health Protection Agency (HPA), the Meteorological Office, the national radiation monitoring network (known as RIMNET), the Food Standards Agency (FSA), the Environment Agency and Government Office for Science – to regular telephone conferences to ensure that information supply was properly co-ordinated. The emergency briefing team was stood down at the beginning of April 2011, with DECC managing the response under normal business arrangements.
- 14 In response to the SoS's request to HM Chief Inspector of Nuclear Installations, 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.

- 15 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?
- 16 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.
- 17 The responses we received up to 31 July 2011 are to be published on our website and the contributions have been considered as part of our work.
- 18 During the production of this report independent nuclear technical advice has been provided to HM Chief Inspector of Nuclear Installations by an ONR Technical Advisory Panel (TAP). Details about the TAP, including its membership and terms of reference are discussed later in this report in the Section "[Technical Advisory Panel](#)".

BACKGROUND

- 19 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 increased by human activities.

General Background

Hazards, Hazard Potential, Barriers and Risks

- 20 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.
- 21 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. If it is in solid form, for it to cause harm to a human being, it has to be inhaled; if it is in massive solid form it is less intrinsically harmful than the same amount of toxic substance in a gaseous form. 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.
- 22 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).
- 23 The existence of a barrier does not mean that we will not suffer harm from the hazard, as the barrier might fail (unless they are founded on the fundamental laws of nature).
- 24 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.
- 25 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. [4](#)).

Radiation, Radioactivity and Risk to Humans from Exposure

- 26 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 nature and 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.
- 27 Radioactive substances can interact with humans through different routes (direct exposure, ingestion, inhalation, or through wounds) and in different ways through different organs where they may accumulate. 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 Radiological Protection (ICRP)) for exposure and harm from ionising radiation.
- 28 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.
- 29 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.
- 30 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. Radiation doses received from exposure to ionising radiation are measured in units of "sieverts" (Sv). A dose of 1Sv 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.
- 31 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, mSv). This is additional to the approximately 2.5mSv 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. 10mSv). 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 installations are 20mSv 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 exposures are substantially below such limits. [Annex C](#) provides some information on typical exposures to ionising radiation from different activities. It should be noted that some exposures can be viewed as voluntary by an individual and others involuntary, and this alters peoples' views on the tolerability of such exposures.

Protection Against Radiation

- 32 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; and
 - 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

- 33 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), such as those involved in the Fukushima accident, 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. In the UK we have one such reactor, at Sizewell B.
- 34 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 three Magnox reactors, two at Wylfa and one 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.
- 35 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 of Japan affected by the 2011 earthquake and tsunami.

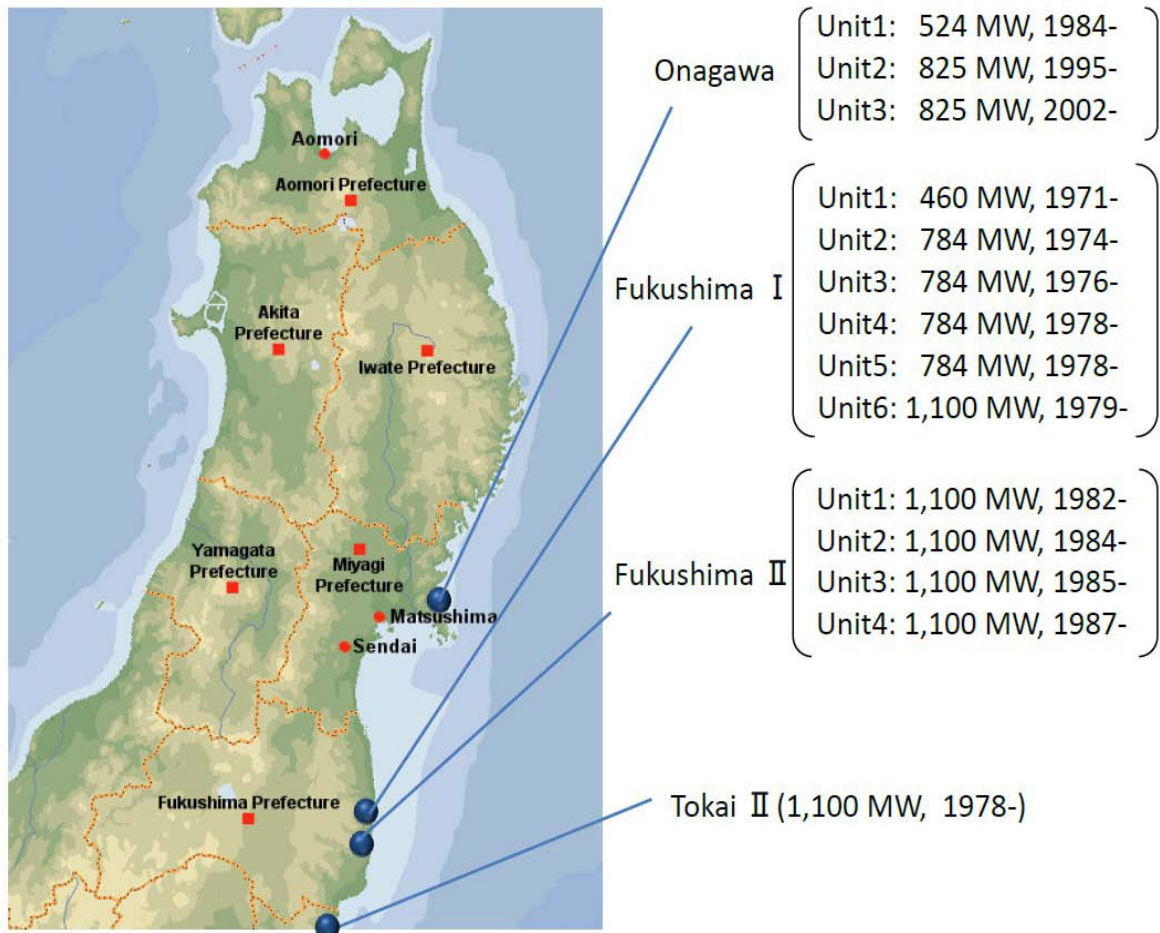


Figure 1: Nuclear Power Reactors in the Area Affected by the 2011 Earthquake and Tsunami
(MW – megawatts electrical output)

Safety of Nuclear Power Reactors

- 36 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.
- 37 To protect against this hazard potential, nuclear power reactor designs employ barriers to preserve all three radiation safety functions – containment, cooling and control.
- 38 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 [Table 1](#) extracted from ONR’s Safety Assessment Principles (SAP) (Ref. [5](#)), 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

39 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. [5](#)).

Probabilistic Safety Analysis and Severe Accidents

40 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.

41 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 (BSL) 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.

- 42 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 the UK to ensure nuclear safety are inherently wrong. Indeed, it is clear that the Japanese did not sufficiently protect against what might be considered a design basis event. 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.

Japanese Nuclear Power Industry

- 43 Japan began to consider the use of atomic energy for peaceful purposes in the 1950s and the first reactor built at the Tokai site was a UK designed Magnox gas-cooled reactor; this commenced operation in 1966. In the 1970s the first water cooled reactors were constructed in cooperation with American companies. General Electric (GE) designed the first two BWR reactor units at Fukushima-1; Reactor Unit 1 was commissioned in 1971. Construction of new plants continued through the following decades, right up to the present day.
- 44 Before the accident at Fukushima-1 there were a total of 54 nuclear power reactor units operating on 17 sites around the coast of Japan. Twenty four of these units are of the PWR type and the other 30 are BWRs. A further two Advanced BWRs are under construction at the Shimane and Ohma sites. There are ten nuclear power plant operating organisations, of which Tokyo Electric Power Company (TEPCO), which owns Fukushima-1 and Fukushima-2 is the largest, with 17 reactor units. On 11 March 2011, when the earthquake struck, 11 reactor units were operating on the four affected sites, these all shut down automatically as designed. [Figure 1](#) in this report shows the four nuclear power sites with operating reactors in the area affected by the earthquake and tsunami; namely Fukushima-1 and Fukushima-2, Onagawa and Tokai. The effects of the consequent tsunami on Fukushima-1 are well documented. Fukushima-2, although inundated by the tsunami, did not lose all electrical power and after a few days all four operating units reached cold shutdown conditions. At Onagawa the observed tsunami height was about 13m, which is below the height of the site and the sea water did not reach the main buildings. Both Onagawa and Tokai experienced some post-shutdown plant-related damage, due to the effects of the tsunami but, subsequently, the four units reached cold shutdown conditions.
- 45 Since the earthquake, all ten units at Fukushima-1 and Fukushima-2 remain shut down. At the time of writing the three BWR reactor units at the Onagawa site and the single operating unit on the Tokai site remain shutdown. In addition, three reactor units operated by Chubu Electric Power Co. at the Hamaoka site (200km south west of Tokyo), which was not directly affected by the earthquake or tsunami, have been closed indefinitely following government concerns over long-standing seismic safety issues. Nineteen of the 54 reactor units in Japan continued to operate beyond 11 March 2011, as they were unaffected by the earthquake or tsunami.

- 46 In early June 2011, the government issued further directions to reactor operators on severe accident management measures to be taken, including hydrogen mitigation measures such as installing re-combiners and cutting holes in reactor buildings.
- 47 The government decided in late June 2011 that in, principle, 38 of the 54 units were safe enough to operate pending implementation of enhanced longer-term severe accident management measures. Government representatives reported that they had taken account of the potential harm to Japan's economy and society from the continued loss of electricity as a result of keeping most of its reactors shut down. In 2010 nuclear power provided 30% of Japan's electricity. The first reactor in Japan since the accident to be authorised by the local authorities to re-start was at the Genkai site in Kyushu. However, on 6 July 2011, in the face of rising public safety concerns and those expressed by some local citizens in Kyushu, the government announced that no reactors will be re-started until they have completed a programme to demonstrate adequate safety levels using an approach based on "Stress Testing".
- 48 The Japanese "Stress Tests" are to be conducted in two phases. The first phase is to be applied to those reactors which are shut down for periodic inspections and maintenance; reported in mid-July to be 35 units. Operators will examine safety margins for postulated large earthquakes and tsunamis, in accordance with guidelines to be provided by the regulatory body. The results of these assessments will contribute to the processes to determine whether a reactor may re-start. The second step will be a more comprehensive risk assessment of all reactors, similar to those being undertaken by European Union (EU) member states. No timetable is available for these tests.
- 49 Other decisions taken in Japan in response to the accident included the cancellation of TEPCO's plan to build Reactor Units 7 and 8 at Fukushima-1. Excluding these units, there remained extant plans to build another 11 nuclear power plants in Japan, taking the proportion of electricity generated by nuclear power to around 50% of total generation.
- 50 At the end of July 2011 there were 19 reactors still operating in Japan, however seven of these were scheduled to be shut down during the summer for statutory maintenance purposes. Reports suggested that if no reactors were re-started in the interim period, then all would be shut down by April 2012.
- 51 There are currently four reactors either undergoing or awaiting decommissioning, these are: two first generation BWRs at the Hamaoka site; the Magnox reactor at Tokai and the Advanced Thermal Test Reactor at Fugen.

Japanese Nuclear Regulatory Regime

- 52 Japan has a national and governmental framework for nuclear safety in place, which largely conforms to international standards and requirements, although not in some important aspects. This framework includes several entities having responsibilities for aspects of regulating nuclear safety. The principal organisation is the Ministry of Economy, Trade and Industry (METI), which is responsible for the regulation of safety of Japanese nuclear installations and has the authority to issue licences to install nuclear installations. The METI 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 programme, including measures to be taken in an emergency. The METI Minister also has the authority to revoke a nuclear licence, order measures to improve operational safety and implement orders relating to emergency preparedness. METI is also engaged in setting energy policy and promoting the use of nuclear energy.

- 53 The Minister of METI delegates regulatory responsibilities to the Nuclear and Industrial Safety Agency (NISA). NISA independently makes decisions or consults with 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 with the separate Nuclear Safety Commission (NSC). This aims to provide enhanced supervision of regulatory decisions.
- 54 The Ministry of Education, Culture, Sports, Science and Technology (MEXT) also has a role for nuclear energy research and development and advice on nuclear safety matters.
- 55 While NSC operates within the Cabinet Office, NISA reports directly to METI.

Nuclear Safety Commission

- 56 NSC is made up of five commissioners appointed by the prime minister, with one being elected chairman. It provides high-level supervision of NISA, which is responsible for delivering the main day to day regulatory functions.

Nuclear and Industrial Safety Agency

- 57 NISA is established to ensure the safety of nuclear installations. Its mission is to ensure the safety of peoples livelihoods through the regulation of the energy and related industries. In carrying out its statutory functions, NISA performs periodic inspections to ensure facilities meet the appropriate requirements and standards. NISA also has a role in regulating nuclear emergency preparedness and response.
- 58 NISA has a total of approximately 370 staff engaged in nuclear safety regulation, out 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 direct comparisons are difficult because of the differing scope of duties.
- 59 NISA has access to an organisation called the Japanese Nuclear Energy Safety Organisation (JNES), which is dedicated to providing it with technical support. JNES is required to maintain strong independent technical expertise and is mandated to carry out specific inspections in support of NISA. This is a mechanism to supplement the resources and staffing available to NISA. JNES employs around 400 personnel.

Commentary on Japanese Regulatory Body

- 60 In 2007 IAEA was invited to peer review the regulatory arrangements in Japan through hosting an Integrated Regulatory Review Service (IRRS) Mission. Although generally judged to be in compliance with international standards, the IAEA reviewers made recommendations where they considered further improvements were possible. These included:-
- The role of NISA as the regulatory body and that of NSC, especially in preparing safety guides, should be clarified.
 - NISA should continue to develop its efforts to address the impacts of human and organisational factors on safety in operation.
 - NISA should continue to foster relations with industry that are frank and open yet formal and based on mutual understanding and respect.

- NISA should ensure that its inspectors have the authority to carry out inspections at the site at any time, to ensure that they have unfettered access rather than only at prescribed inspection times.

- 61 Not specifically cited by the IAEA IRRS mission is the current reporting line of NISA within government to the promotional ministry METI and the apparent free movement of senior personnel between regulatory authorities (NSC and NISA), METI and TEPCO, the largest operating organisation. These issues have attracted adverse media coverage implying a potential conflict of interest and a degree of regulatory capture.
- 62 Some media reports suggest that scientists from the Atomic Energy Society of Japan have expressed the view that the existence of multiple regulatory oversight groups made responsibilities unclear and may have hampered response in the wake of the accident. They appear to be calling for a unified regulatory body, which does not rely excessively on establishing precedent to guide their assessment of risk from operation of nuclear plants. Subsequent statements attributed to Japanese officials at two conferences convened by the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD) and IAEA in June 2011 indicate that METI will lose its responsibilities for regulating nuclear safety. It seems that the independence of the regulatory body will be enhanced through transfer from METI to another entity, the details of which are yet to be determined.
- 63 In early 2011 NISA approved a ten year life extension to the oldest of the reactors on the Fukushima-1 site. Information in respect of the operator's safety case that was used to justify the life extension to the Japanese regulators is not available in the UK. A report, published in April 2011 by German operators' association VGB Power Tech (Ref. [6](#)), implies that Japanese nuclear regulators failed to require operators to protect their plants against reasonably foreseeable natural phenomena. The VGB Power Tech report suggested that the safety margin of the Fukushima-1 plant for protection against tsunamis was not sufficient.
- 64 In support of its views, VGB Power Tech cites that the 14m high tsunami that inundated Fukushima was by no means an unusual or highly improbable occurrence for Japan. It tabulates historical details of earthquake induced large tsunamis (i.e. greater than 10m high) originating off the coast of Japan. These occur on average every 30 years. The reported Fukushima-I design basis appears on this evidence never to have been adequate.
- 65 The UK ONR SAPs recommend protection against faults caused by natural hazards, such as earthquakes and tsunamis, at a predicted frequency of occurrence of up to once in every 10,000 years. Postulated initiating events meeting this requirement are considered in the design basis for nuclear installations in the UK. Available information suggests that the data used to design flood protection for the Fukushima-1 site were not required to meet similar limits.
- 66 In late May 2011 IAEA conducted a fact-finding Mission to Japan to gather information and make a preliminary assessment of the circumstances surrounding the accident at Fukushima-1. IAEA provided, in its preliminary report (Ref. [7](#)), a view that the tsunami risk for several sites had been underestimated. In addition, it made a general finding that nuclear regulatory systems should address extreme events adequately, including their periodic review, and should ensure that regulatory independence and clarity of roles are preserved in all circumstances. These initial findings were confirmed in the final IAEA report presented to the Ministerial Conference convened by IAEA in Vienna in late June 2011. The IAEA report also concluded that a follow-up IRRS mission should be conducted in Japan to assist in the further development of its regulatory regime. The Japanese government said in its report to the IAEA Ministerial Conference that NISA would be split from METI and combined with other agencies to form an independent regulatory body.

- 67 Furthermore, in July 2011, the prime minister of Japan commented that NISA being part of METI, which also promotes nuclear power, potentially conflicted with independent enforcement of nuclear safety requirements before Fukushima. He confirmed that NISA would be separated from the direct influence of the ministry sponsoring nuclear power.
- 68 It has now been reported that the Japanese government has agreed to establish a new nuclear safety regulatory body that will combine the functions of both NSC and NISA, and will report instead to the Environment Ministry. The new body is expected to be fully operational by April 2012.
- 69 The Japanese government has set up a special independent “Investigation Committee on the Accidents at the Fukushima Nuclear Power Station of TEPCO” to review all of the circumstances surrounding the accident. The investigation will include the role the regulatory body and its bearing on the events at Fukushima. The Investigation Committee plans to submit its report by the end of 2011 and to make it available to the public.

Technology Used at the Fukushima-1 Site

- 70 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 in the Section entitled “[Role and Relevance of Key Reactor Systems During the Fukushima Accident](#)”. In general, the information regarding BWR technology provided in this section of the report has been extracted from Refs [8](#), [9](#) and [10](#), and from discussions with experts on BWR technology.
- 71 Although all the Fukushima-1 reactor units are BWRs designed by GE, there are design differences between them. Key characteristics of the six units (Ref. [2](#)) are given in [Table 2](#).

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.

- 72 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.

BWR Cooling Cycle

- 73 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 moisture separator, where water droplets are removed, and then it passes through a steam dryer before entering 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 sea water passing through the secondary side. Once condensed, the water is pumped back into the reactor vessel starting the cycle again ([Figure 2](#)).

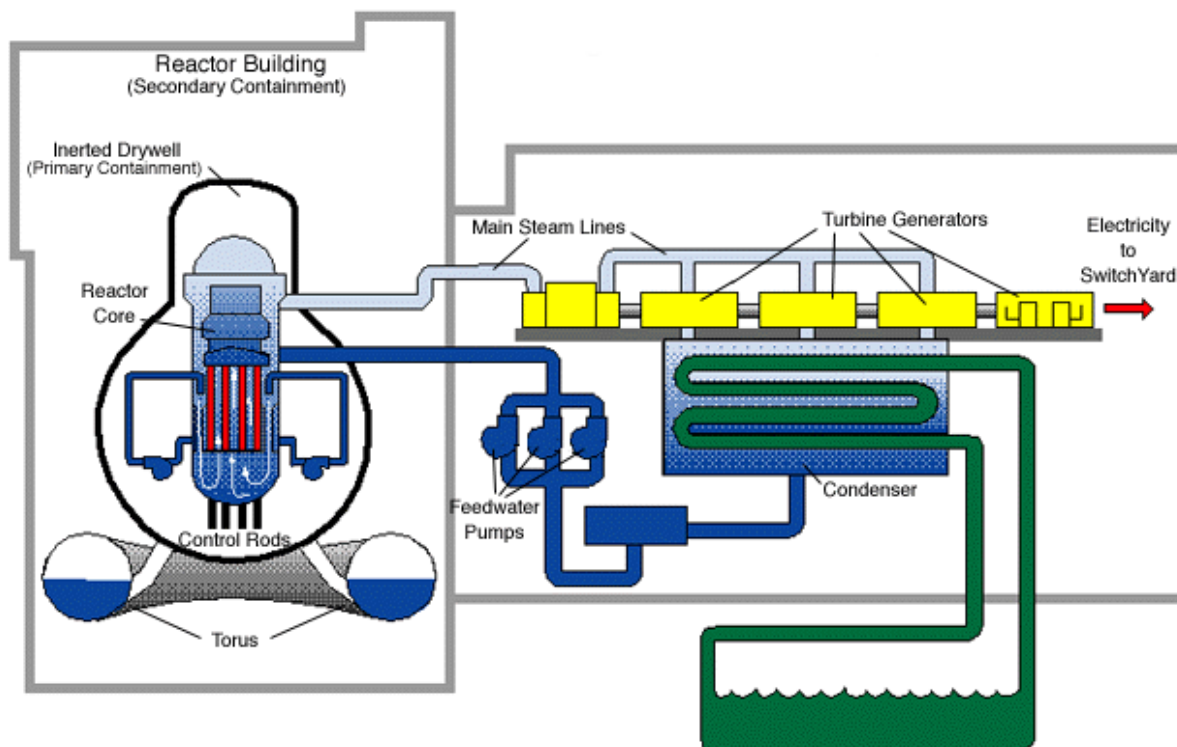


Figure 2: Cooling Schematic of a Boiling Water Reactor (*figure courtesy of GE Hitachi Nuclear Energy*)

Reactor

74 The BWR 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 70 times atmospheric pressure.

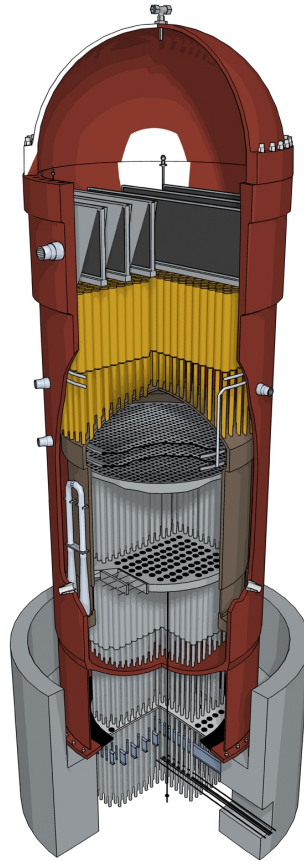


Figure 3: Boiling Water Reactor Vessel (*figure courtesy of GE Hitachi Nuclear Energy*)

- 75 The reactor core is made up of fuel assemblies, control rods and neutron monitoring instruments. [Figure 4](#) shows a BWR control cell consisting of a control rod of cruciform shape and four fuel assemblies surrounding it. Each BWR fuel assembly consists of fuel rod bundles enclosed in a fuel channel which directs coolant upwards.



Figure 4: Boiling Water Reactor Fuel Assemblies and Control Rod Module (figure courtesy of GE Hitachi Nuclear Energy)

- 76 Each fuel rod consists of a metallic cladding made of a zirconium alloy housing the nuclear fuel, which is in the form of small ceramic pellets, made of uranium dioxide, stacked up inside the cladding.
- 77 To control the flow of coolant through the core, and to change the reactor power level relatively quickly, 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 (RPV).

Containment

- 78 The RPV 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.
- 79 Fukushima-1 Reactor Units 1 to 5 have a Mark I containment with a drywell that resembles the shape of a light bulb ([Figure 5](#)). The Mark I drywells are built of steel and lined on the outside with reinforced concrete with an average thickness in excess of 1.5m.

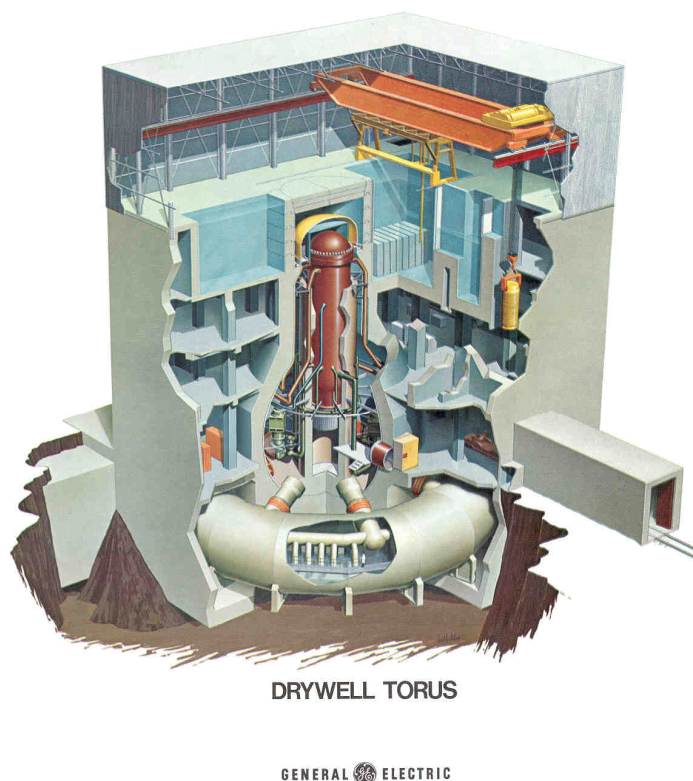


Figure 5 Schematic Cut-away of Mark I BWR (figure courtesy of GE Hitachi Nuclear Energy)

- 80 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.
- 81 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. The drywell and the torus are designed to withstand the same pressure. There is an interconnecting vent network between the drywell and the suppression chamber (Figure 5). The function of these vents is to channel steam from the drywell to the suppression pool (in case of a loss of coolant accident). These vents are surrounded by sleeves and have expansion joints (or bellows) to accommodate displacements between the drywell and the suppression chamber. These bellows are designed to withstand high pressure, but this could be the limiting pressure of the primary containment.
- 82 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 6](#)). As for the Mark I containment, the drywell and the suppression chamber are designed to withstand the same pressure.

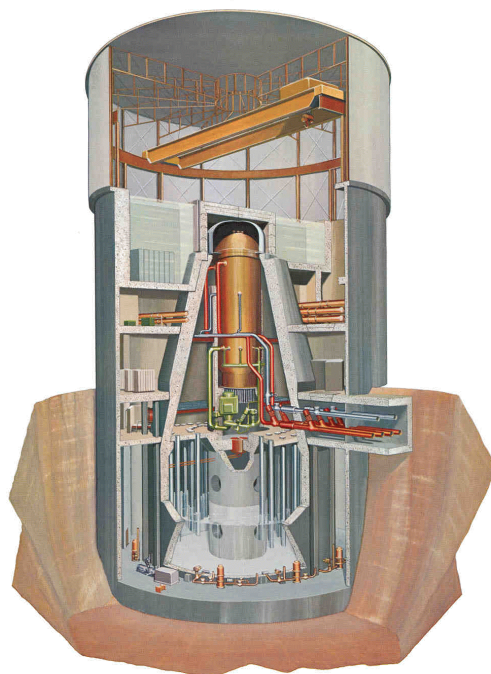


Figure 6: Schematic Cut-away of Mark II BWR (*figure courtesy of GE Hitachi Nuclear Energy*)

- 83 Each of the Fukushima-1 reactors was housed in a reactor building that serves as a secondary containment. The reactor building surrounds the primary containment (drywell and suppression chamber) and houses the emergency core cooling systems and the spent fuel pool ([Figure 5](#) and [Figure 6](#)).
- 84 The reactor building in the Mark I model is kept under negative pressure using the ventilation system as long as AC power is available. This is so that any leaks from the primary containment are contained and any releases can be controlled. Therefore, the safety role of the secondary containment is to minimise releases of radioactive materials to the atmosphere and to provide a controlled filtered release at some height under certain accident conditions. While the same arrangements may apply to the reactor buildings in the Mark II models, we have not been able to confirm this.
- 85 The secondary containment in the Mark I models can be made of concrete all the way through (believed to have been the case at some of the Fukushima-1 reactor units) or can have upper walls made of metal panels (like the one at Fukushima-1 Reactor Unit 1). The secondary containments are tested to demonstrate that they are leak-tight and therefore both design types are, in principle, equally capable of complying with their safety role. It is worth noting that these reactor buildings are fitted with relief mechanisms that offer protection against overpressure. It seems that in the Fukushima-1 reactor buildings this function was provided by some blow-out / relief panels on the walls (as observed in photographs of Reactor Unit 2 whose reactor building was not damaged by explosions).

86 The top floor of the reactor building is the service floor from which the refuelling of the reactor is conducted. In both [Figure 5](#) and [Figure 6](#) one can observe a large metallic structure held on railings; this is the service floor crane (also referred to as reactor 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, see [Figure 5](#)) is removed using the crane, and located in a designated area on the service floor as shown in the photographs of Ref. [11](#). The RPV head is then removed.

Spent Fuel Storage

87 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 the need to develop 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).

88 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. In due course, at Fukushima-1, fuel is transferred to a central large spent fuel pool. 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.

89 Spent fuel at the Fukushima-1 site is, therefore, 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 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 (Ref. [12](#)).

90 Overall, 60% of the spent fuel on-site was stored in the common pond, 34% of the spent fuel was in the reactor ponds and the remaining 6% was in the dry storage facility.

UK NUCLEAR INDUSTRY

- 91 In this report we are concentrating on those elements of the industry related to nuclear power and some defence facilities. We recognise that there are other work-related activities that involve use of radioactive materials, such as hospitals and some laboratories, but these are not included here.

UK Nuclear Power Industry

- 92 The UK operates the following reactors:

Table 3: 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

- 93 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 AGRs use enriched uranium dioxide fuel with stainless steel cladding. All Magnox reactors having steel pressure vessels were safely shut down in a phased manner at the end of their lives by the end of 2006.
- 94 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 RPVs. These later designs had significant safety advantages over the steel pressure vessels since a sudden and unexpected failure of the main pressure vessel boundary is considered virtually impossible.
- 95 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.[§]

- 96 The UK's gas-cooled reactors do not need secondary containment. None of the design basis loss of coolant accidents precipitates 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 (LBLOCA) results in significant fuel failure and release of radioactive fission products.
- 97 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 Non-nuclear Power Plant Nuclear Facilities

Sellafield

- 98 The Sellafield site in Cumbria is the location of a number of significant UK non-Nuclear Power Plant (NPP) facilities. The facilities on the site include several diverse operational facilities and a number of facilities undergoing decommissioning. The site comprises both the Sellafield and Windscale nuclear licensed sites operated by Sellafield Limited (the licensee) and owned by the Nuclear Decommissioning Authority (NDA).
- 99 Operations on the Sellafield site began in the 1940s, when the site was a Royal Ordnance factory supporting the war effort. Nuclear operations commenced on the site with initial fuel loading of the two Windscale Piles in 1950 and construction of the facilities for the separation of fissile material from the spent fuel. The site later became home to the world's first commercial nuclear power station – Calder Hall – which operated four Magnox reactors successfully from 1956 to 2003. A further reactor, the Windscale Advanced Gas-cooled Reactor (WAGR) was constructed and commissioned as a prototype for the UK's second generation of reactors. WAGR ceased operating in 1981. All seven of these reactors are now in differing stages of decommissioning, with WAGR now essentially complete. (The four reactors at Calder Hall have been considered within this report and within the European Council "Stress Tests" as NPPs since they still hold spent fuel in their reactor cores).
- 100 Operations on-site today centre around the nuclear fuel cycle, with two spent fuel reprocessing plants, i.e. the Magnox Reprocessing Plant and Thermal Oxide Reprocessing Plant (THORP). The reprocessing facilities are supported by a number of waste and effluent treatment plants and associated storage facilities. Nuclear fuel manufacturing was until recently carried out on the Sellafield site at the Sellafield Mixed Oxide Fuel (MOX) Plant (SMP). SMP was built to return reprocessed fissile material in the form of mixed oxide fuel to overseas customers.
- 101 The main focus for the Sellafield site is now reducing the risk by moving radioactive hazard from a number of legacy facilities across the site to more robust more modern facilities and accelerated decommissioning of the legacy facilities.

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

Dounreay

102 The licensed nuclear site at Dounreay on the far north coast of Scotland is owned by the NDA and operated by Dounreay Site Restoration Limited (DSRL), the site licence company charged with the closure of what was Britain's centre for fast reactor research and development. Construction of the Dounreay Materials Test Reactor (DMTR) and Dounreay Fast Reactor (DFR) started in 1955, followed by construction of the 250MWe Prototype Fast Reactor (PFR) which achieved criticality in 1974. DMTR was shut down in 1969, DFR in 1977 and PFR in 1994. The site also housed fast reactor fuel reprocessing plant as well as a materials test reactor fuel manufacturing plant, together with associated waste handling plant and laboratories. Reprocessing ceased in 1996 and fuel fabrication in 2004. DMTR has been de-fuelled and is currently in a care and maintenance state. PFR has been de-fuelled and its liquid metal removed, with fuel currently stored within the PFR complex pending treatment. DFR retains one fuel element and a large number of breeder elements, with its liquid metal coolant currently being removed prior to removal of all fuel elements. Used and unused nuclear fuel is stored on-site, together with liquid reprocessing liquors and other waste. Decommissioning of the reactors and other plant is due to continue to the "interim end state" currently scheduled for 2025-32.

Winfrith

103 Winfrith, located in Dorset, was a centre for UK civil reactor research and development from the 1950s to the 1990s. It is now owned by the NDA and operated, together with Harwell, by Research Sites Restoration Limited (RSRL), the site licence company charged with the closure of the site. The site operated a number of reactor types, the biggest of which (in terms of power) was the Steam Generating Heavy Water Reactor (SGHWR), which was shut down in 1995. Eight reactor types were operated in all. They have all been de-fuelled and decommissioned with the exception of SGHWR and Dragon, a high temperature gas-cooled reactor. SGHWR and Dragon are currently defuelled and in a state of care and maintenance pending further decommissioning. Site activity, in addition to decommissioning, includes waste storage and handling. No fuel is stored on-site.

Harwell

104 Harwell was established in Oxfordshire 1946 as the UK's atomic energy research establishment. The newly established United Kingdom Atomic Energy assumed responsibility for the site in 1954. The site is now operated, together with Winfrith, by RSRL, the site licence company charged with the closure of the site. It operated a number of research reactors, the last of which were shut down in 1990. Site activity, in addition to decommissioning, includes waste storage and handling. Some spent fuel is stored on-site.

Springfields

105 The Springfields licensed site near Preston has provided nuclear fuel fabrication services since the mid-1940s. In 2005, responsibility for the assets and liabilities of the site transferred to the NDA. A new company, Springfields Fuels Limited, was created to run the site, managed and operated by Westinghouse Electric UK Limited on the NDA's behalf. Subsequently, Westinghouse acquired a long-term lease for the Springfields site, which transferred responsibility for the commercial fuel manufacturing business and Springfields Fuels Limited to Westinghouse.

- 106 The site's activities include manufacture of oxide fuels for advanced gas-cooled and light water reactors, manufacture of uranium hexafluoride, processing of residues, decommissioning and demolition of redundant plants and buildings.

URENCO UK

- 107 The URENCO UK (UUK) site near Chester operates three uranium enrichment plant that produce enriched uranium for sale to customers world-wide. In addition to enrichment activity, the site stores depleted uranium hexafluoride.

Capenhurst (Sellafield Limited)

- 108 The Capenhurst (Sellafield Limited) site is located adjacent to the UUK site and is owned by the NDA. It formerly housed the UK's first generation gaseous uranium enrichment plant. The site is now being decommissioned. It stores depleted uranium hexafluoride and uranium oxide.

Low Level Waste Repository

- 109 The Low Level Waste Repository (LLWR) at Drigg in Cumbria is the UK's national low level waste disposal site.

Metals Recycling Facility

- 110 The Metals Recycling Facility owned by Studsvik UK was licensed in 2008 to carry out processes for de-contaminating and recycling metal waste as part of the UK's National Low Level Waste (LLW) strategy. The site is in Cumbria.

Imperial College Consort Reactor

- 111 Imperial College operates a low power research reactor at Ascot. It is at the early stages of a decommissioning programme.

GE Healthcare Limited Sites

- 112 GE Healthcare Limited (GEHC) has three nuclear licensed sites in the UK; the Grove Centre at Amersham; the Maynard Centre at Cardiff and a Building at Harwell. GEHC operations centre on the manufacture of radiopharmaceutical products. The Grove Centre is currently implementing its decommissioning plan whilst the Maynard Centre is also undergoing decommissioning. GEHC's former waste packaging facility and source manufacture operations at Harwell have ceased, and activities now relate to post-operational clean-out.

Defence Nuclear Licensed Sites

- 113 There are seven nuclear site licences held by five companies who, under contract to the Ministry of Defence (MoD), deliver nuclear weapons and naval nuclear propulsion strategic defence programmes. Each licensee has been working closely with other defence licensees and the wider

nuclear industry through the Safety Directors' Forum to ensure adoption of a consistent approach when replying to HM Chief Inspector of Nuclear Installations' Interim Report recommendations.

- 114 The nuclear weapons programme is centred at the Atomic Weapons Establishment (AWE) at Aldermaston and Burghfield in Berkshire. AWE manufactures and maintains the warheads for the UK's Trident submarine-launched nuclear deterrent.
- 115 The Naval Nuclear Propulsion Programme (NNPP) covers three areas:
- Submarine reactor fuel manufacture which includes a test reactor research facility
 - Submarine construction and commissioning
 - Submarine maintenance and refuelling.
- 116 Rolls Royce Marine Power Operations Limited (RRMPOL) in Derby, Derbyshire, carries out the manufacture of nuclear fuel for submarine reactor plant. They also operate a low energy naval research reactor.
- 117 BAE Systems Marine Limited (BAESM) at the Devonshire Dock Complex at Barrow-in-Furness, Cumbria carries out submarine construction and commissioning activities. Currently the Astute Class hunter killer submarines are being built for the Royal Navy.
- 118 Devonport Royal Dockyard Limited (DRDL) in Plymouth, Devon carries out the maintenance and refuelling of the Royal Navy's submarines. Plant and site modifications are currently being progressed that will enable future defuelling activities to be carried out on redundant hunter killer submarines.
- 119 Most of the nuclear-related facilities at Rosyth Royal Dockyard Limited (RRDL) in Fife have been decommissioned and there remains only a small inventory of radioactive waste. None of the decommissioned submarines presently berthed at Rosyth contains nuclear fuel.

Defence Nuclear Non-licensed Sites

- 120 There are several naval sites where nuclear-related activities occur which are under the control of the Crown (MoD) and so are excluded from the need for licensing under the Nuclear Installations Act 1965 (as amended). These sites operate under an authorisation regime regulated by the Defence Nuclear Safety Regulator (DNSR), although ONR also regulates the sites through the Health and Safety at Work etc. Act 1974 and associated legislation, including the Ionising Radiations Regulations 1999 and Radiation (Emergency Preparedness and Public Information) Regulations 2001. These authorised sites are HM naval bases at Devonport and Clyde (which comprises the Faslane and Coulport sites) and the Vulcan Naval Reactor Test Establishment at Dounreay. ONR works jointly with DNSR at these sites, where our responsibilities coincide. DNSR has issued instructions to these authorised sites following Fukushima which are similar in requirements to HM Chief Inspector of Nuclear Installations' Interim Report recommendations (Ref. [13](#)).

UK NUCLEAR REGULATORY REGIME

Legal Framework

- 121 In the UK, the legal framework for nuclear safety is established principally through two pieces of legislation. These are the:
- Health and Safety at Work etc. Act 1974 (HSWA74); and
 - Nuclear Installations Act 1965 as amended (NIA65).
- 122 Under HSWA74, employers are responsible for ensuring, so far as is reasonably practicable, the safety of their workers and the public. This responsibility is elaborated further in relation to nuclear sites by NIA65, which provides for a nuclear site licensing regime. The power to grant a licence to use a site to construct and operate a specified nuclear installation, and consequently for its regulation, is invested with the HSE, which further delegates this authority to HM Chief Inspector of Nuclear Installations.
- 123 In addition other relevant statutes are in force, providing more detailed requirements relating to safety; notable amongst these are the:
- Ionising Radiations Regulations 1999 (IRR99); and
 - Radiation (Emergency Preparedness and Public Information) Regulations 2001 (REPPIR).
- 124 The regulatory framework for managing the environmental impact 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. In addition, the Nuclear Reactors (Environmental Impact Assessment for Decommissioning) Regulations 1999 ensure appropriate environmental impact assessments are undertaken prior to decommissioning.
- 125 European legislation in the form of European Commission Directives is transcribed into the UK legal framework outlined above. The most recent European legislation is the Nuclear Safety Directive, which came into force in July 2011.

Department of Energy and Climate Change

- 126 DECC and its minister is responsible to parliament for nuclear safety matters. In addition it 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 (CNS), 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.
- 127 In carrying out its responsibilities, DECC will, where appropriate, seek information on nuclear safety-related matters from ONR and advice on environmental issues from the environment agencies.

Office for Nuclear Regulation

- 128 ONR is the principal regulator of the safety and security of the nuclear industry in the UK and its independence is secured legally through HSWA74 and NIA65. It was established as a non-statutory agency of the HSE on 1 April 2011. ONR's reporting line within government is through HSE, sponsored by the Department for Work and Pensions (DWP).
- 129 ONR is mainly comprised of the old Nuclear Installations Inspectorate, UK Safeguards Office and the former Office for Civil Nuclear Security. In addition to nuclear safety, security and safeguards, ONR has recently taken on the nuclear regulatory functions of the Department for Transport (DfT) by incorporation into ONR of the DfT Radioactive Materials Transport Team.
- 130 ONR is responsible for licensing and regulating a broad range of facilities and activities, from nuclear power plants, atomic weapons sites, nuclear chemical facilities, to decommissioning plants and site remediation. The main safety functions of ONR are to grant and administer the nuclear site licence, inspect, and review and assess the safety of plant, people and processes on licensed nuclear sites. ONR has the primary responsibility for regulating radioactive waste accumulated and stored on licensed sites. ONR is also involved in setting safety standards both nationally and internationally.
- 131 ONR does not use a dedicated technical support organisation as some other regulators do. Much of the necessary technical expertise, across a wide range of technical areas, is available to ONR through its own experienced personnel. Additional technical support, where necessary, is provided through other specialist organisations, such as HSE's Health and Safety Laboratory or other pre-qualified suppliers. The technical support organisations provide information to ONR; it is for ONR to make any regulatory decisions.

Environment Agencies

- 132 The Environment Agency and Scottish Environment Protection Agency (SEPA) are the environmental regulators for nuclear sites in England, Wales and Scotland. These organisations are responsible for authorisation of the disposal of radioactive wastes from nuclear licensed sites and other environmental permits.
- 133 ONR has the primary responsibility for regulating radioactive waste accumulated and stored on licensed sites, and through memoranda of understanding the Environment Agency and SEPA cooperate with ONR 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, permissioning waste generating activities, or if a variation to a nuclear site licence is necessary, and it is related to or affects the creation, accumulation, control, containment or disposal of radioactive waste.
- 134 Periodically the Environment Agency and SEPA carry out joint inspections with ONR on nuclear sites and undertake joint investigations into the circumstances surrounding significant incidents, as appropriate. The environment agencies also carry out environmental monitoring around nuclear sites.

Health Protection Agency

- 135 HPA was established on 1 April 2005 under the Health Protection Agency Act 2004, replacing the HPA Special Health Authority and the National Radiological Protection Board (NRPB), with radiation

protection as part of health protection incorporated in its remit. Since 1 April 2010, the NRPB role is performed by the Centre for Radiation Chemical and Environmental Hazards (HPA-CRCE). Its statutory functions include 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 from radiation risks. In addition HPA-CRCE provides technical services, information and advice to persons concerned with radiation hazards.

ONR Regulatory Approach

- 136 The regulation of 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 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 a single licence may cover the lifetime of an installation.
- 137 NIA65 allows HM Chief Inspector of Nuclear Installations to attach to each nuclear site licence such conditions as he 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 Licence 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 safety areas identified. The Licence Conditions provide the legal basis for regulation of safety by ONR. They do not relieve the licensee of the responsibility for safety. They are mostly non-prescriptive and set goals that the licensee is responsible for achieving.
- 138 One of the main functions of ONR is to carry out inspections at licensed sites, at the licensee's corporate headquarters, and elsewhere. These enable ONR to check compliance with nuclear site licence Licence Conditions and other legal requirements. Inspection 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 principle of ensuring risks are ALARP. A suite of Technical Inspection Guides (TIG) is used by ONR Inspectors to assist them in planning for and undertaking regulatory inspections at licensed sites.
- 139 One of the requirements of the Licence Conditions is that the licensees produce an adequate safety case. The safety case is a fundamental part of the licensing regime at all stages in the life-cycle 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.
- 140 ONR has developed and published its own technical principles, which it uses to judge licensees' safety cases; these are set out in the SAPs (Ref. 5). The latest version of the SAPs, published in 2006, was benchmarked against extant IAEA safety standards and is consistent with the Western European Nuclear Regulators' Association (WENRA) reference levels. In addition to the SAPs, more detailed Technical Assessment Guides (TAG) are available to ONR assessors to assist them in making judgements on licensees' safety submissions. In the areas relevant to the accident at the Fukushima-1 site, the SAPs and TAGs set out regulatory expectations for protection against hazards such as extreme weather, flooding, earthquakes, fire, explosion etc., and for provision of essential services (see the Section "[Protection of Fukushima-1 Reactor Units against Natural Hazards and the Impact of the Events](#)" for more details). Additional comments are made in the Section

[“Recommendations Relevant to the Regulator \(ONR\) – Recommendation IR-5”](#) in relation to the adequacy of the scope and depth of the ONR SAPs.

- 141 In the UK the operator of a nuclear installation is also required by the Licence Conditions to have arrangements to periodically review its safety case for the plant. This Periodic Safety Review (PSR) usually takes place every ten years 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 in the review. If the PSR identifies any reasonably practicable safety improvements, then these should be made by licensees. In addition, life-limiting factors that would preclude operation for a further ten years should also be identified in the review. ONR independently assesses licensees’ PSR reports using its SAPs and TAGs. Examples of safety upgrades made following PSRs include those in relation to improved seismic resistance for older plants that may not have been designed with earthquakes in mind.
- 142 The UK has been subject to two international peer reviews of its regulatory infrastructure by IAEA through their IRRS. The first IRRS mission in 2006 (Ref. [14](#)) focused on the preparedness to regulate new build. During this mission the IAEA team recognised the UK nuclear safety regulatory system as mature and transparent, with an advanced review process, and with highly trained, expert and experienced staff. It also found that the Nuclear Installations Inspectorate (now ONR) was internationally recognised for its contribution to safety regulation. Thirteen areas of good practice were identified in the 2006 report, along with some areas to strengthen its regulation.
- 143 The second IRRS mission in 2009 (Ref. [15](#)) reviewed progress against the findings of the first mission and assessed some new aspects of how HSE’s Nuclear Directorate (now ONR) regulates operating nuclear facilities. In the second mission, IAEA found that HSE’s Nuclear Directorate has made significant progress toward improving its effectiveness in regulating existing nuclear power plants and in preparing to assess new nuclear reactors designs in a changing and challenging environment. IAEA also reviewed transition plans for HSE’s Nuclear Directorate to become an independent Statutory Corporation. The IRRS team supported the approach to transition to Statutory Corporation status. In addition, ONR contributes actively to IAEA’s development of Safety Standards and the IRRS was highly complimentary in this regard. The second IRRS report included a number of new good practices as well as recommendations and suggestions to help strengthen the UK regulatory body.
- 144 The then IAEA Deputy Director General said: *“It is so timely and vitally important to implement the UK Government’s decision to set up HSE Nuclear Directorate as an autonomous, more independent, well resourced nuclear regulator. This is the UK showing an encouraging example to all in the world in preparing for the challenges of the future.”*
- 145 Intermediate steps towards this aim of an autonomous, more independent, regulator have already been taken with the formation of ONR as an agency of HSE.

UK NUCLEAR EMERGENCY ARRANGEMENTS

- 146 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

- 147 This section of the report provides an overview of the Fukushima accident, with an updated account of the key events and the impact on the plant and its surroundings.

Summary

- 148 The situation at the Fukushima-1 site remains serious and work continues to bring the various facilities to a stable and safe state. It is likely that enquires and investigations will be on-going for many months and years to come, which will reveal new details, clarifications and corrections to the information presented below. However, this section represents ONR's current understanding of the sequences of significant events at Fukushima from publicly available sources. The Interim Report (Ref. [1](#)) relied predominantly on press releases by TEPCO, NISA and IAEA produced contemporaneously with events unfolding at the site. Since then, the Japanese government has produced a more considered and definitive report (Ref. [2](#)), which is the prime source for the details presented below, along with the report of the IAEA fact-finding mission to Japan (Ref. [3](#))
- 149 When the earthquake struck, off-site power from the grid was lost (mainly due to the collapse of pylons connecting the site to the wider grid and some off-site switchgear) 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). The re-established AC power was effectively lost when the tsunami hit the site, deluging the switch gear and all but one of the on-site diesel generators. Many cooling functions, including to the majority of the diesels, were lost due to the effect of the tsunami on the sea water pumps. Reactor Unit 1 was also stricken by loss of DC power because its batteries were flooded (Reactor Unit 2 also lost some functionality provided by DC power).
- 150 Further details and key factors are below. Only the events in the first few days and weeks of the accident following the earthquake and tsunami, while the operators battled to retake control of the situation, are discussed here. The recovery phase and on-going efforts to bring the site to a sustainable safe state are not discussed.

Timeline of Key Events

- 151 The earthquake sequence that affected and continues to affect the Fukushima site started with a magnitude 7.3 event on 9 March 2011, which was followed within a few hours by a series of large seismic events. The main shock, of magnitude 9.0 (known as the Tohoku event), occurred on 11 March 2011 at 14:46 local time. There have been over 500 aftershocks with a magnitude greater than 6. The most important of these were the magnitude 7.4 and 7.7 events on 11 March 2011 and 7.1 on 7 April 2011. The geographical spread of aftershocks and other associated quakes has been very extensive and due to a newly recognised phenomenon – crustal “dynamic overshoot” – has involved many large events distant from the original rupture zone, including some in-land.
- 152 The initial fault rupture had its origin (hypocentre) at a depth of around 24km, 180km 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. The initial rupture appears to have lasted for 60 seconds, focused around the hypocentre before spreading both north and south and continuing for a further 110 seconds. The waveforms measured at the Fukushima site show two separate phases of strong motion, with the second phase generating a larger peak acceleration

than the first. 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/year, and begins its westward descent beneath Japan at the Japan Trench. Japan has a long history of large earthquakes. Although the Tohoku event was the largest in the historical record of Japan, earthquakes of similar magnitude, or greater, occur somewhere in the world on average every 15–20 years: On that basis it was the 5th largest recorded in the past 100 years. The previous largest earthquakes in Japan were the Great Kanto event (M_L 8.3) of 1923 and the Meiji-Sanriku event (M_L 8.5) of 1896. Both of these events caused significant damage and large numbers of fatalities.

- 153 The first tsunami wave resulting from the main shock arrived at the Fukushima-1 site at around 15:41 local time on 11 March 2011, and the second wave at 15:35 local time just under an hour after the earthquake.

Impacts of the Earthquake on the Site

- 154 The effects on the site were measured in the basements of the six reactor units at between 0.33g^{**} and 0.56g peak horizontal acceleration (see [Figure 7](#)). 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.
- 155 On a broader scale, there was an overall downward permanent displacement of the coastline elevation, with estimates varying between 0.5 and 1.2m.
- 156 It is clear from [Table 4](#) that the observed horizontal accelerations are broadly of the same order as the basic ground motion anticipated 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. The on-going situation at the plants has prevented detailed inspection of many of the structures and systems. 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., but the extent of any initial seismic damage to other plant items, such as pipework, cannot be determined at this stage.
- 157 The Fukushima-1 reactor units are fitted with an automatic shut down system linked to ground motion instrumentation. The reactor shut-down levels were set at the reactor units at around 0.14g horizontally and around 0.1g vertically (Ref. [16](#)). These levels were encountered early on in the event, and the available data is consistent with the system having worked and that shut down was initiated via the seismic trip.
- 158 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. [17](#)).
- 159 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

- 160 The two main tsunami waves arrived at the Fukushima site between 15:27 and 15:35 local time on 11 March 2011. The site was rapidly inundated to depths up to 6m.

^{**} g denotes the acceleration due to gravity. 1g = 9.81ms⁻²

- 161 Information provided by TEPCO (Ref. [18](#)) 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 (Reactor Units 1–4) and +13m (Reactor Units 5 and 6). The estimated height of the tsunami wave is at about OP +14–15m. The inundation depth adjacent to the reactor buildings for Reactor Units 1–4 and turbine buildings is therefore in the range of 4–5m, but may locally have been up to 6m.
- 162 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.
- 163 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.
- 164 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 sea water intake were severely damaged. The site was left littered with debris.
- 165 The extremely long wavelength (and consequently period) of tsunami waves means that the site remained inundated for a period of between 30 minutes and an hour following the main wave arrival.
- 166 [Figure 7](#) shows the 2011 earthquake and tsunami alongside other recently recorded events off the east coast of Japan.

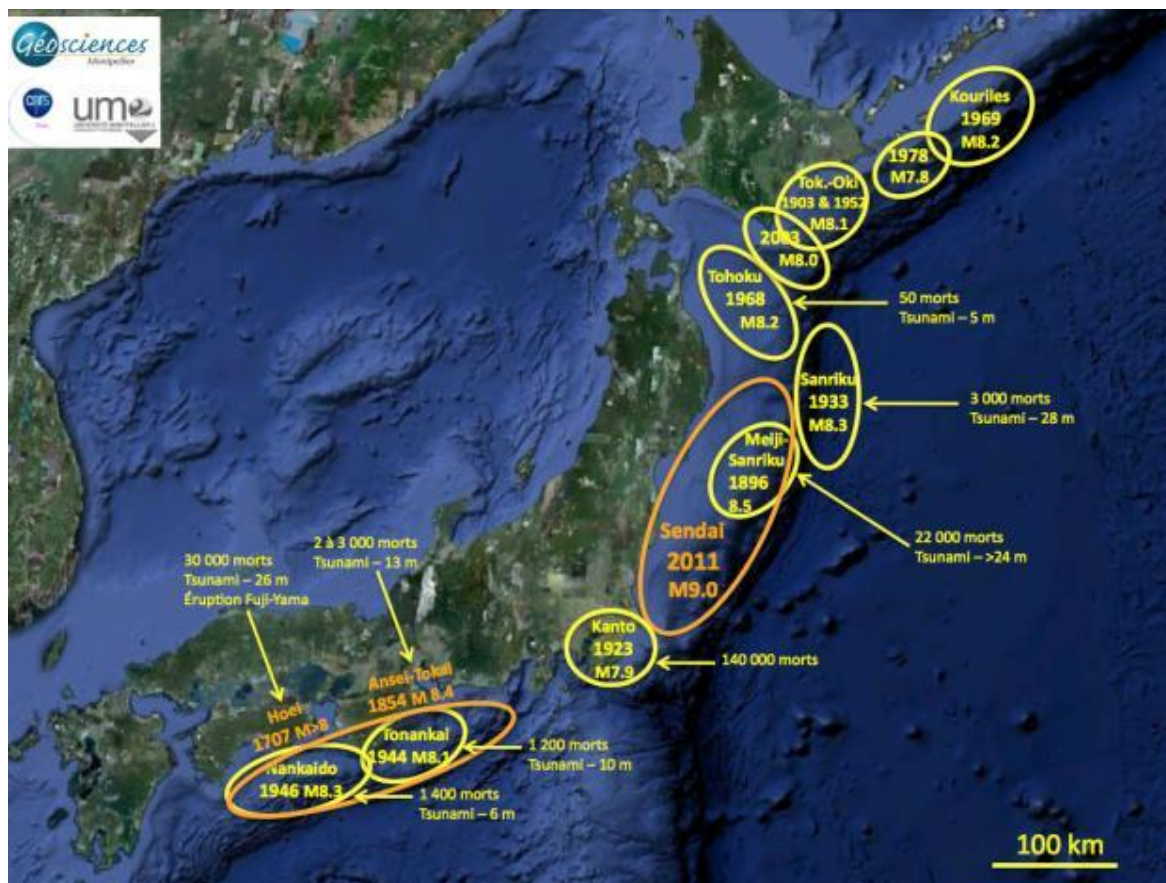


Figure 7: Earthquake and Tsunami Data for Events off the East Coast of Japan.

Broader Impact on Local Area Around the Site

- 167 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. External power to the Fukushima site was lost as a result of failures of pylons, landslides affecting transmission lines, and damage to circuit breakers and insulators.
- 168 In many places the tsunami was more disruptive than the earthquake, with inundation reaching many kilometres inland and affecting an area of up to 600km². The buildings and infrastructure of many towns and villages have been completely destroyed, with debris scattered over a large area. The statistics from the Japan Fire Department (Situation Report No. 135, Ref. 19) suggest 16,500 fatalities, 4780 missing, nearly 6000 injured, 112,000 destroyed buildings, 140,000 partially destroyed buildings and 520,000 partially damaged buildings. The damage and disruption created significant problems in the first few days following the events for access to the Fukushima-1 site for specialist equipment and personnel.

Conditions at Fukushima-1 Prior to the Earthquake

169 Reactor Units 1, 2 and 3 were operating at power when the earthquake struck while the Reactor Units 4, 5 and 6 were already shut down. Reactor Unit 4 was in a periodic inspection outage with all its fuel off-loaded to its pond to allow the core shroud to be replaced. Reactor Units 5 and 6 had a full complement of fuel in their respective RPVs despite being shut down. Reactor Unit 5 was undergoing RPV pressure leak tests at the time of the earthquake while Reactor Unit 6 was in cold shutdown conditions. The inventory in the respective ponds is shown in [Table 3](#), taken from Ref. [20](#):

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

Sequence of Events in Reactor Unit 1

- 170 Reactor Unit 1 successfully shut down automatically when the earthquake struck at 14:46 local time on 11 March 2011. Despite the loss of the external power, its two emergency diesel generators automatically started to provide AC power to the unit. The loss of external power triggered the Main Steam Isolation Valves (MSIV) to shut off (as designed), preventing steam generated by the reactor from reaching the turbines. The Isolation Condenser automatically started up to take over the heat removal function and seemed to have operated correctly under manual control to achieve the required RPV cool-down rate. The Primary Containment Vessel (PCV) spray systems were also operated during this initial period to cool the suppression chamber. There is no indication that the High Pressure Coolant Injection System (HPCI) activated (or was needed to operate) prior to the tsunami arriving.
- 171 Reactor Unit 1 felt the effects of the tsunami at 15:37 local time. The water stopped the operation of the emergency diesel generators, with the emergency bus distribution panel being submerged and the switch gear and sea water pumps damaged. Reactor Unit 2 was similarly affected, so its power supply was not available to support Reactor Unit 1.
- 172 Reactor Unit 1 lost DC (battery) power functions due to the tsunami so it was not possible for operators to check parameter information. This meant they were unable to monitor the reactor water level and had no clear idea of the water injection situation. They had also lost sea water cooling (the ultimate heat sink) due to the damage to sea water pumps and the loss of power.
- 173 Following the tsunami, TEPCO attempted to restart the Isolation Condenser function by opening a valve in the system and using a diesel-driven fire pump to pump freshwater into the body of the Isolation Condenser. However, investigations several weeks after the initial event were unable to establish the degree to which the valve was open and, therefore, whether the Isolation Condenser was able to provide any effective cooling following tsunami.

- 174 Reactor Unit 1 was designed with an HPCI to maintain the water levels in the RPV. It is not clear why this proved ineffective, but is thought to be related to the loss of batteries and hence DC electrical supplies to its control system. It is discussed further in the Section "[Role and Relevance of Key Reactor Systems During the Fukushima Accident](#)".
- 175 The operators started to pump freshwater through fire pumps to the RPV at 05:46 local time 12 March 2011. Assuming that the cooling function of the Isolation Condenser was lost at 15:37 the previous day, the reactor had been without pumped cooling water for over 14 hours.
- 176 TEPCO concluded in the early hours of 12 March 2011 that there was a possibility that the PCV pressure had exceeded its maximum operating pressure and informed NISA in accordance with the established protocols. As a result, at 06:50 local time, the Regulator ordered TEPCO to take measures to reduce the pressure in the PCV. To this end, TEPCO managed to manually open a motor operated valve in the PCV vent line to 25% at about 09:15 local time 12 March 2011. Despite high radiation levels they strove to open a second, air operated, valve in the subsequent hours. These attempts were judged to be successful because the PCV pressure had reduced by 14:30 local time.
- 177 At 15:36 local time an explosion, presumed to be a hydrogen explosion, occurred in the upper part of the reactor building. The roof, the outer wall of the operation floor and the waste processing building roof were destroyed. Radioactive material was released by the explosion, increasing the radiation dose in the surrounding area.
- 178 At 14:53 local time, just prior to explosion, it was established that the supply of 80,000 litres of fresh water being injected into the RPV had been exhausted. The reactor was subject to several more hours without any water injection before TEPCO started to inject sea water into the RPV using fire fighting lines at 19:04 local time on 12 March 2011.
- 179 It will be months or years before the exact status of the reactor core and vessels can be determined, but computer modelling performed by both TEPCO and NISA suggests that Reactor Unit 1's core was exposed two to three hours after the earthquake, suffered damage in the subsequent hour, and the RPV would have failed in five to 15 hours after the earthquake. The current assumptions (based on this analysis rather than observations) are that the fuel has melted and a considerable amount is lying at the bottom of the RPV. However, if the RPV has failed as predicted, some fuel may have dropped and accumulated in the drywell. Computer modelling of the expected severe accident phenomena is discussed further in [Annex L](#).
- 180 On 25 March 2011, sea water injection was replaced by fresh water. The fire fighting pumps supplying this injection were replaced by a temporary electric pump on 29 March 2011, and on 3 April 2011 the power supply for this pump was improved by replacing a temporary arrangement with a permanent supply.
- 181 Ref. [2](#) states that by 31 May 2011, an estimated 13,700 tonnes of water had been injected into the RPV but only 5,100 tonnes could have been converted to steam even with the most limiting estimates of decay heat. The capacity of the RPV is only 350m³ so it is assumed that the pressure boundary is no longer intact, allowing liquid as well as steam to leak.
- 182 The PCV exceeded its maximum working pressure on 12 March 2011 and temperatures in the drywell exceeded the measurable maximum (greater than 400°C). Ref. [2](#) concludes from this that gaskets and flanges will inevitably have weakened, compromising the pressure boundary function of the PCV.

- 183 Radioactive materials contained within the fuel prior to the accident would have been released into the RPV as the uncovered fuel became damaged and subsequently melted. The PCV venting operations are assumed to have released all noble gases originating from the damaged fuel. Analysis by TEPCO and NISA, making judgements on leakage rates from the RPV and PCV, predicts that the release ratio radioactive nuclides (the amount of radioactive nuclides released compared to the total amount of a particular nuclide present in the reactor core) in the region of 1% for iodine, tellurium and caesium
- 184 To prevent hydrogen gas mixing with oxygen inside the PCV, and hence to reduce the risks of further explosions, TEPCO have been injecting nitrogen into the PCV since 7 April 2011.

Sequence of Events in Reactor Unit 2

- 185 Like Reactor Unit 1, Reactor Unit 2 successfully shut down automatically when the earthquake struck at 14:16 local time on 11 March 2011 and its two emergency diesel generators automatically started to provide AC power to the unit. Its MSIVs automatically shutoff as a result of the loss of external power. The design of Reactor Unit 2 is different to that of Reactor Unit 1 in that it has the Reactor Core Isolation Cooling System (RCIC) and not an Isolation Condenser. The RCIC on Reactor Unit 2 was started manually in accordance with procedures following the rise in RPV pressure which followed from the closure of the MISVs. In the period between the reactor shutting down after the earthquake and the tsunami hitting the site nearly an hour later, the RCIC was started and stopped through a combination of manual and automatic actions and appears to have successfully maintained the reactor water level above the fuel in the core.
- 186 Reactor pressure was controlled during this period by the opening and closing of a Safety Relief Valve (SRV). The combined effect of the SRV opening and the RCIC operation was an increase in the suppression chamber temperature. Residual Heat Removal (RHR) pumps started sequentially at 15:00 local time and 15:07 local time to cool the suppression chamber which successfully reduced the rate of temperature rise.
- 187 Records show that the RHR pumps started shutting down from around 15:36 local time, presumed to be due to the tsunami. The two emergency diesel generators also stopped and, with the submergence of the sea water cooling system pumps, the power distribution panel and the emergency bus bar, the unit entered station blackout. Furthermore, information on many plant parameters could not be verified due to a loss in DC functionality.
- 188 The RPV injection continued for some days with the turbine-driven pumps supplying water to the reactor and the steam being dumped into the suppression chambers through spargers. This caused the temperature and pressure in the primary containment vessel to rise steadily.
- 189 At 22:00 local time on 11 March 2011 the operators managed to obtain an observation of the reactor water levels which indicated that the RCIC operation was maintaining a steady level. From 04:20 to 05:00 local time on 12 March 2011, the water source for the RCIC was switched from the condensate storage tank to the suppression chamber to maintain injection (the condensate storage tank was depleting while the suppression chamber level had increased). This action was sufficient to maintain a stable, level, water level in the reactor above the fuel until 11:30 local time on 14 March 2011. After that point, the water level started to drop. Later that day, at 13:25 local time, the RCIC was judged to have shut down and by 16:20 local time the water level in the reactor was determined to have dropped to the top of the fuel. The RCIC is steam driven but its valves require DC currents (see Section [“Role and Relevance of Key Reactor Systems During the Fukushima](#)

[Accident](#)”). It appears to have continued to function longer than expected given the assumed constraints on battery capacity.

- 190 Operations to open a SRV to reduce reactor pressure (to facilitate alternative water injection) commenced at 16:34 local time on 14 March 2011, resulting in an observed drop in reactor pressure at around 18:00 local time. However, reactor pressure started to rise again, attributed to the air driven SRV closing due in part to problems with air pressure. At 19:54 local time that day, sea water injection into the RPV using fire engines started. The core had therefore been without water injection for approximately 6.5 hours since the RCIC lost functionality.
- 191 TEPCO were ordered by their Regulator to take actions to reduce the PCV pressure at 06:50 local time on 12 March 2011. Ref. [2](#) states that TEPCO undertook operations to attempt this but by the end of 14 March 2011 no decrease in the drywell pressure could be verified. At around 06:00 local time the sound of an impact, assumed to be a hydrogen explosion, was heard on the site. No visible damage was observed at the reactor building. It has been commonly assumed that the explosion occurred in the vicinity of the suppression chamber but at the time of writing no inspections of the area have been possible to corroborate this assumption. It is unclear whether the hydrogen release was associated with a leak developing in the containment or with venting operations.
- 192 Sea water injection continued until 26 March 2011, at which point it was replaced by fresh water injection from a temporary tank. The next day it was possible to replace the fire pumps with temporary motor-driven pumps, and from 3 April 2011 it was possible to replace the temporary power supply with an external power supply.
- 193 Computer modelling by TEPCO and NISA using the best information they have on the extent of water injection following the earthquake predicts that the core became exposed at around 17:00 local time on 14 March 2011 and core damage started approximately two hours later (approximately 75 hours after the earthquake). The computer analyses are not unanimous in predicting RPV failure. Depending on the assumptions made and the computer codes used, predictions have been made of RPV failure five hours after core exposure, 34 hours after core exposure, and also of no RPV failure at all. More detailed discussion is provided in Annex L.
- 194 TEPCO estimated that by 31 May 2011 they had injected 21,000 tonnes of water into the RPV but the maximum amount of this water which could be converted to steam by the fuel’s decay heat is about 7,900 tonnes. As the RPV volume is only 500m³, the pressure boundary must have been damaged, with liquid as well as steam leaking. From 16 March 2011, the RPV was at close to atmospheric pressure and equal to the drywell pressure, therefore there must be a connection between the RPV and the PCV in the vapour phase area. Temperature measurements of the RPV at around 150°C were made after 29 March 2011. This is slightly above the saturation temperature of water at the recorded RPV pressure, and may indicate that there are still significant amounts of fuel in the RPV but it is not all submerged in water.
- 195 The drywell pressure exceeded the maximum usable pressure on 15 March 2011. Japanese authorities presume that at this point the sealing performance of the flange gaskets and penetrations deteriorated. The drywell maintained a pressure close to atmospheric despite all the steam generated in the RPV, and therefore it is assumed that it was no longer providing secure containment. It has been difficult for TEPCO to determine the status of the suppression chamber, but Ref. [2](#) implies from the high levels of contaminated water in the turbine hall that there is a route for water injected into the RPV through the PCV.

- 196 The uncovering of the core would inevitably have generated a large amount of hydrogen. TEPCO has estimated that an amount equivalent to the reaction of about 80% of the fuel cladding would have been generated in the first week.
- 197 The estimates of release rates vary. All the noble gases are assumed to have been released. Iodine release rates between 0.4% and 7% have been estimated, 0.4% to 3% for tellurium nuclides, and 0.3% to 6% for caesium.
- 198 To prevent hydrogen gas mixing with oxygen inside the PCV and hence to reduce the risks of further explosions, TEPCO have been injecting nitrogen into the PCV since 28 June 2011 (Ref. [21](#)).

Sequence of Events in Reactor Unit 3

- 199 Reactor Unit 3 successfully shut down automatically when the earthquake struck on 11 March 2011. External power was lost but its two emergency diesel generators started automatically. The loss of external power triggered the MSIVs to close (as designed) at 14:48 local time. The RCIC started manually at 15:05 local time in accordance with procedures following the rise in RPV pressure which followed on from the closure of the MSIVs. The RCIC was stopped at 15:28 local time with a high water level measured in the reactor.
- 200 At 15:38 local time the arrival of the tsunami resulted in the emergency diesel generators stopping, loss of all AC power, switchgear and the emergency bus bar of Reactor Unit 3. The cooling sea water pumps were also lost. The DC bus of Reactor Unit 3 did survive the tsunami, allowing backup storage batteries to supply some key equipment (e.g. RCIC valves and instrumentation) longer than was possible on other units.
- 201 Ref. [2](#) reports that the RCIC, which had been deliberately stopped a few minutes before the tsunami hit, was restarted at 16:03 local time and operated until 11:36 local time on 12 March 2011. It is not known why the RCIC stopped, but it is expected that the storage batteries required to manipulate the RCIC valves would have been exhausted after 20 hours of RCIC operation. The HPCI started automatically at 12:35 local time on 12 March 2011, prompted by the detection of low water levels in the core, and ran till 14:42 local time the next day. The water level in the reactor core at the time when the HPCI stopped is not known. At 15:31 local time, power was restored to the water level gauge, which showed that the water level was substantially below the top of the core (-1600mm).
- 202 Following the loss of the HPCI, TEPCO vented from the suppression chamber at 08:41 local time on 13 March 2011. At 09:25 local time, the operators started injecting fresh water dosed with boric acid through the fire extinguishing system driven by fire engine pumps. Despite this, the RPV water level still dropped. Even if credit is taken for this seemingly not altogether effective injection, the reactor core had been without injection for six hours and 43 minutes after the HPCI had stopped. At 13:12 local time on 13 March 2011, water injection was changed to sea water. A further wet vent was performed at 05:20 local time on 14 March 2011 to reduce the RPV pressure.
- 203 At 11:01 local time on 14 March 2011, an explosion, presumed to be a hydrogen explosion, occurred in the upper part of the reactor building. The explosion destroyed the operation floor and all floors above it, the north and south external walls of the floor below the operation floor, and the waste processing building. The radiation dose in the vicinity of the site increased and radioactive materials were released into the atmosphere (in addition to those released through deliberate venting).

- 204 It has not been possible to determine the exact status of the reactor core and vessel but computer analysis by TEPCO predicts that the fuel rods in the reactor core would have become exposed about four hours after the HPCI stopped at 14:42 local time on 13 March 2011, and damage to the core would have started in a further two hours. Despite the injection of water through the fire extinguish system from 09:25 local time, the computer modelling suggests that the RPV would have been damaged after a further day of inadequate cooling and low water levels. Computer modelling by NISA makes similar predictions.
- 205 The same analyses estimate that all the noble gases would have been released to the environment by the PCV vent operations. Predictions of the amount of radioactive iodine released vary between 0.4% and 0.8%. NISA predictions for caesium and tellurium are similar (i.e. less than 1%).
- 206 On 25 March 2011, it was possible to switch from sea water injection to fresh water. Three days later, it was possible to use temporary motor-driven pumps for the reactor injection and, on 3 April 2011, their power supply was provided by a permanent source.
- 207 Ref. [2](#) states that, by 31 May 2011, an estimated 20,700 tonnes of water had been injected into the RPV, but only 8300 tonnes could have been converted to steam even with the most limiting estimates of decay heat. As the capacity of the RPV is about 500m³, it is assumed that the pressure boundary of the vessel is no longer intact and liquid as well as steam can leak from it. The RPV pressure has been measured as close to atmospheric pressure since 22 March 2011, so it is assumed that there must be a connection between the RPV and PCV in the vapour phase area.
- 208 RPV temperatures exceeded the measurable range (higher than 400°C) on 20 March 2011 but dropped to around 100°C with a consolidation of the injection flow rate on 24 March 2011. This suggests that a considerable amount of reactor fuel remains in the RPV despite the predictions of RPV failure. In May, temperatures above 200°C were recorded for the depressurised RPV which is above the saturation temperature, indicating that part of the reactor fuel is not underwater and is being cooled by vapour only.
- 209 The pressure in PCV had exceeded the maximum operating pressure by 13 March 2011. From this point, it is assumed that the performance of the flanges and penetration seals deteriorated. This is consistent with the measurements of atmospheric pressure in the drywell, despite the steam generated by the water injection into the RPV.
- 210 To prevent hydrogen gas mixing with oxygen inside the PCV and hence to reduce the risks of further explosions, TEPCO have been injecting nitrogen into the PCV since 15 July 2011 (Ref. [22](#)).



Figure 8: Post Accident Photograph of Reactor Units 1-4 at Fukushima-1

Reactor Unit 1 to 4 Fuel Ponds

211 It is not known what level of damage the fuel ponds sustained in the initial earthquake. The evidence to date seems to suggest that the structures of the (reactor) fuel ponds remained essentially intact. However, in the absence of any active cooling of the ponds following the loss of the power and the damage to the sea water pumps 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 spent fuel remains covered, even if the water is boiling, the radiological threat from a fuel pond is relatively small. However, once uncovered, it is unlikely that the fuel will be cooled sufficiently to prevent some of 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.

- 212 The last temperature reading from Reactor Unit 4's pond was 84°C at 04:08 local time on 14 March 2011 (Ref. [2](#)). 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 11:01 local time on 14 March 2011. At approximately 06:00 local time on 15 March 2011 TEPCO confirmed an explosive sound and damage around the 5th floor rooftop area of the reactor building (Ref. [2](#)). It is reasonable speculation to assume that the structures associated with the 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 was no definitive information at the time on whether these were attributable to spent fuel fires (zirconium burns with a light grey smoke) or to another source in the vicinity of the pond.
- 213 The cause of the explosion in Reactor Unit 4 has still not been clearly identified. Camera inspections and analysis of the nuclides in the water carried out several weeks after the explosion revealed no evidence of extensive damage to the fuel rods – see [Figure 9](#).



Figure 9: Condition of the Spent Fuel Pool (Reactor Unit 4)

- 214 Visual inspections also did not reveal any significant water leaks or cracks in the pond's structure. These findings are not supportive of the assumption made at the time of a hydrogen explosion resulting from fuel uncover. Other explanations have been proposed such as that hydrogen generated by reactor core damage in Reactor Unit 3 could have flowed into the building of Reactor Unit 4, or that the explosion was not caused by hydrogen. However, at the time of writing, no definitive mechanism has been established.

- 215 It is expected that future investigations will establish that Reactor Unit 3's pond also suffered some mechanical damage in the explosion of 14 March 2011 or at another time during the event. No temperature data from Reactor Unit 3's pond was published during the weeks following the event. 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% of the fuel assemblies Reactor Unit 4 had, and they had been cooled longer since its refuelling outage. Camera inspections of Reactor Unit 3's pond have revealed substantial amounts of debris in the water and covering the top of the fuel.
- 216 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. [23](#)). 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.
- 217 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 the spent fuel pool cooling line from 25 March 2011 (the cooling line was only providing make-up 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.
- 218 This provision of make-up water to the fuel ponds seems to have been effective in maintaining the water levels and protecting the fuel, although there was not constant monitoring of the temperatures and water levels in the weeks following the earthquake in all the units. It is known that much more water was directed towards the ponds (Reactor Units 3 and 4 especially) than their capacity.
- 219 Significant levels of iodine-131 and caesium-137 were detected at sampling points away from the Fukushima-1 site. While some caesium-137 would be released from 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 suggest that the radiological consequences from the Fukushima-1 site due to airborne releases have so far been dominated by the releases from the reactors and not from the fuel ponds. This is discussed further in the Section "[Spent Fuel Pond Factors During the Fukushima Accident](#)".

Reactor Units 5 and 6

- 220 Both Reactor Units 5 and 6 were shut down at the time of the earthquake (Reactor Unit 5 since 3 January 2011, Reactor Unit 6 since 14 August 2010). They are located slightly away from Reactor Units 1 to 4 and appear to have suffered less damage. Despite being already shut down, they still required active cooling for both the reactors and the ponds to remove decay heat.
- 221 External power was lost with the initial earthquake on 11 March 2011 but the two emergency diesel generators at Reactor Unit 5 and the three emergency diesels at Reactor Unit 6 started automatically. At 15:40 local time the tsunami resulted in the emergency diesel generators and sea water pumps of the RHR on Reactor Unit 5 being lost, and two of the three diesel generators on Reactor Unit 6 being lost, along with its sea water pumps. However, one diesel generator, located

relatively high and away from the turbine building, survived the tsunami and, because it was air-cooled, it remained in operation despite the loss of sea water cooling. Additionally, it had its own local protected supply of diesel fuel.

- 222 Reactor Unit 5 had been performing RPV pressure leak tests (with fuel in the core) at the time of the earthquake. The loss of power caused the equipment applying the pressure to the reactor to stop, resulting in a temporary pressure drop from its test level of 7.2MPa. Over the next few hours the decay heat caused the RPV pressure to increase to around 8MPa. The operators took actions to reduce the RPV pressure at 06:06 local time on 12 March 2011, but the pressure continued to increase moderately.
- 223 The pressure in Reactor Unit 6 increased moderately after the tsunami but the rate of increase was more modest than Reactor Unit 5 as it had been shut down for longer (despite it being a larger design, the time elapsed since the initial shut down meant the decay heat remaining in the core was less).
- 224 On 13 March 2011, water was successfully injected into both Reactor Unit 5 and Reactor Unit 6 using condensate transfer pumps powered from the operating emergency diesel generator on Reactor Unit 6. Over the next few days, the reactor pressure and water level were controlled by opening an SRV and repeatedly refilling the RPV with water from the condensate storage tank.
- 225 On 19 March 2011, temporary sea water pumps were provided to the RHR systems on Reactor Units 5 and 6. This allowed the spent fuel ponds and the reactors to be alternately cooled by switching the mode of the RHRs. The Reactor Unit 5 achieved cold shutdown at 14:30 local time on 20 March 2011 and Reactor Unit 6 achieved the same status at 19:27 local time later the same day. The fuel pond temperatures also rapidly returned to acceptable levels (Ref. [23](#)).
- 226 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. [23](#)).

Restoration of Off-site Power

- 227 When a nuclear power station is operating, it generates its own electricity to power its essential systems and services. However, once it is shut down, 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 all operating reactors on-site shut down in response to the earthquake. The subsequent tsunami resulted in a loss of all but one of the 13 emergency diesel generators. TEPCO therefore expended a significant amount of effort to restore power on-site through a re-establishment of a grid connection.
- 228 The following key events have been identified in NISA briefings (Ref. [23](#)) for Reactor Units 1 to 4:
- Reactor Unit 1 – Lighting recovered in central control room at 11:30 local time on 24 March 2011. RPV injection switched to off-site power at 12:12 local time on 3 April 2011.
 - Reactor Unit 2 – Power Centre received power at 15:46 local time on 20 March 2011. Lighting in Central Operation Room established at 16:46 local time on 26 March 2011. RPV injection switched to off-site power at 12:12 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 12:18 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

- 229 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. [24](#)). 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 re-started the same day (Ref. [23](#)). This rapidly brought the temperatures down to normal levels.
- 230 It is a concern that so little was known about the status of facility with such a large radioactive inventory for a prolonged period of time. It is understood that the fuel was transferred to the common pond after at least 19 months of cooling in the reactor ponds (Ref. [12](#)). With a week without active cooling, the water temperature only rose by approximately 27°C despite the pond being close to capacity. It is not clear if this modest temperature rise can be linked directly to the 19 month requirement or if it was just a fortuitous outcome of recent operations (i.e. an operation still in compliance with the 19 month cooling requirement could have resulted in a much higher temperature increase). The IAEA fact-finding mission visited this area and did not observe any significant damage.

Dry Cask Storage Facility

- 231 The dry cask storage building is located not far from the sea, in the path of the tsunami. The IAEA mission (Ref. [3](#)) reported that the tsunami damaged the building and inundated it to a level of 10m, but the casks appeared to be intact. Radioactive monitoring has not shown any release so it appears the casks are unaffected.

Role and Relevance of Key Reactor Systems During the Fukushima Accident

- 232 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. In addition, severe accident management measures had been studied and implemented in all reactor units (Ref. [25](#)). 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, mainly by the 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.
- 233 In general, the information regarding BWR technology provided has been extracted from publicly available information in Refs [8](#), [9](#) and [10](#) and from discussions with experts on BWR technology. Specific details about the reactors at Fukushima-1 have been obtained from Ref. [2](#). Since the publication of the Interim Report in May 2011 we have actively sought information to enhance 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 progression of the accident sequences. However, it has to be acknowledged that it is not yet possible to present information that is totally precise and complete.
- 234 In order to appreciate the relevance of the information provided in this section it is necessary to indicate up front that the BWR technology itself appears not to have had a particular significance in the chain of events that started on 11 March 2011. Therefore, lessons can be sought in relation to the safety of nuclear installations in Britain despite the fact that there are no reactors of the same or similar technology in operation in the UK.

Reactivity Control

- 235 BWRs are unique in that the control rods used to control the rate of nuclear fission and to shut down 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 shut down the BWRs. In the Interim Report we already indicated that it was believed that the control rod systems actuated automatically and 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 had been reported. Information provided later, in Ref. [2](#), confirms this.
- 236 The penetrations of the control rods through the bottom of the RPV may act as a particular route for material to escape from the core under severe accident conditions, although this may not be the most likely failure mode of the RPV under those circumstances. From information in Chapter IV of Ref. [2](#), based on the results of the computer modelling carried out by TEPCO and NISA (as discussed in the Section "[Timeline of Key Events](#)"), it is believed that the reactor cores in Reactor Units 1, 2 and 3 would have melted, and a certain amount of molten fuel debris could be outside the RPVs accumulated on the drywell floor. This scenario could have occurred due to failures of Control and Instrumentation (C&I) penetrations, creep rupture of the bottom of the RPV or failures of the penetrations of the control rod driving mechanisms. Further discussion about the progression of the severe accidents at the three units is provided in [Annex L](#) and in Refs [26](#) and [27](#).
- 237 BWRs have a diverse system to shut down the reactor called standby liquid control system. This system injects a "neutron poison" (boron) into the reactor vessel to shut down 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.

Normal Post-trip Cooling

- 238 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 kW electrical fires). This decay heat decreases very quickly initially and then slower and needs to be removed to avoid the reactor core overheating. 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.
- 239 The shutdown cooling mode of the 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. According to Table IV-2-1 and Figure IV-2-2 of Ref. [2](#) at Fukushima-1 Reactor Units 2 and 3 the RHR system had two trains, each with two pumps and one heat exchanger. A simplified diagram of the system is shown in

Figure IV-2-9 of the same report. It should be noted that this system had other modes of operation and functions which are discussed in the Sections on "[Low Pressure Emergency Core Cooling Systems](#)" and "[Containment Cooling](#)".

- 240 At Fukushima-1 Reactor Unit 1, the RHR function, after any normal reactor trip or programmed shut down, was undertaken by a system called the Reactor Shutdown Cooling System (SHC). A simplified diagram of the system is shown in Figure IV-2-8 of Ref. [2](#). According to Table IV-2-1 of Ref. [2](#) at Fukushima-1 Reactor Unit 1 this system had two pumps and two heat exchangers. It appeared to take suction from one of the re-circulation loops upstream of the re-circulation pump and discharge to the other re-circulation loop downstream of the re-circulation pump. Also, from Table 1-1 of Attachment IV-3 of Ref. [2](#), it is inferred that the SHC at Fukushima-1 Reactor Unit 1 could receive emergency power supply from the diesel generators although the principal function of this system was to cool the shutdown reactor under normal operational circumstances (i.e. non-accidental) conditions. This would have provided additional functionality to the system although in the Fukushima accident this was of no particular relevance since the diesel generators were also lost due to the tsunami. According to the same table, the SHC system could also be used to cool the spent fuel pool.
- 241 From Tables 1-1, 1-2 and 1-3 of Attachment IV-3 of Ref. [2](#) it is clear that the SHC heat exchangers (Reactor Unit 1) and RHR heat exchangers (Reactor Units 2 and 3) were cooled by sea water cooling systems. No specific details have been found about the design of the cooling chain to the final heat sink for the three Fukushima-1 reactors units. Therefore, it is not clear whether the SHC / RHR heat exchangers were cooled directly by the sea water systems, or whether any of the units had an intermediate closed-loop fresh-water cooling system with separate heat exchangers cooled themselves by the sea water systems.
- 242 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. In addition, as indicated earlier in this report, cooling functions were lost due to the impact of the tsunami on the sea water pumps. Thus RHR / SHC cooling would have not been an available option.
- 243 In contrast to Reactor Units 1 to 3, at the time of the event, the temperatures in the reactors in Reactor 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 damage to the reactor cores. Once power and temporary sea water cooling pumps were established, these reactors were returned to a situation called "cold shutdown" on 20 March 2011 and have remained in that state since, and they are not discussed further in this part of the report.
- 244 As Reactor Unit 4 had been defuelled to its pond, there were no requirements for post-trip cooling. This reactor unit is not discussed further.
- 245 The following sub-sections therefore focus on the Fukushima-1 units that suffered reactor accidents, i.e. Reactor Units 1, 2 and 3. Also, the information provided mainly concentrates on the role and performance of systems during the hours after the earthquake until it becomes apparent that the reactor cores had overheated and degraded, which was accompanied by evidence of severe accident phenomena, such as hydrogen explosions. Any further recovery activities, and the means and systems used for that purpose, are not discussed in this part of the report.

Reactor Pressure Control

- 246 Fukushima-1 Reactor Units 1 to 3 had an Automatic Depressurisation System (ADS). The ADS consists of a number of automatically activated relief valves that depressurise the reactor vessel to allow actuation of the low-pressure injection systems. The ADS valves open upon receipt of a “very low reactor level” signal together with a “high drywell pressure” signal (there may be differences in the ADS actuation signals among the different BWR models). ADS valves can also be actuated manually. ADS valves discharge into the suppression chamber, which provides a filtering function for any fission products discharged. From information provided on page IV-7 of Ref. [2](#) at Fukushima-1 Reactor Units 1 to 3 the ADS function was provided by the safety relief valves, SRVs (described in the following paragraphs). The automatic depressurisation function of the SRVs has been briefly discussed here for completeness, but it did not play any role in the progression of the accidental sequences.
- 247 According to Table VI-2-1 and Figures IV-2-6 and IV-2-7 of Ref. [2](#), Fukushima-1 Reactor Units 1 and 2 were fitted with air-operated SRVs with dual function as follows:
- “Relief-valve function” which is actuated by relevant signals from the C&I systems, or manually, and for which air (or nitrogen) pressure and DC power supply are required.
 - “Safety-valve function” which is mechanically self-actuated on high system pressure.
- 248 The SRVs (four valves at Reactor Unit 1 and eight valves at Reactor Unit 2) discharged into the suppression chamber. The set-points for their “safety-valve function” were between approximately 76.5 and 78bar.
- 249 According to Table VI-2-1 and Figure IV-2-7 of Ref. [2](#), Fukushima-1 Reactor Unit 3 was also fitted with eight SRVs discharging into the suppression chamber. However only the set-points for their “relief-valve function” are provided, i.e. their “safety-valve function” set-points are not included in the table. This may be an omission rather than an indication of a design difference.
- 250 Fukushima-1 Reactor Units 1 to 3 also had Safety Valves (SV) (mechanical / spring actuated) to provide protection against significant reactor overpressure. The steam released gets discharged into the atmosphere of the drywell. According to Table VI-2-1 of Ref. [2](#), each of Fukushima-1 Reactor Units 1, 2 and 3 had three safety valves venting to the drywell at pressures above 85bar.
- 251 According to Table VI-2-1 of Ref. [2](#), the set-points for the “safety-valve function” of the SRVs in Reactor Units 1 and 2 were considerably lower than for the SVs, which would be the last ones that would open in case of reactor overpressure, and only in case of failure or insufficient capacity of the SRVs. In this regard, and according to Figure 3.1.2 in Attachment IV-1 of Ref. [2](#), it seems that the analysis performed by TEPCO with the MAAP code has predicted that the set-point of the SVs would not have been reached at Fukushima-1 Reactor Unit 1. On the other hand, the same plot seems to show little peaks and dips in RPV pressure somewhere above 75bar, suggesting that the SRVs would have been cycling for some hours; we have no reason to believe that the real behaviour was significantly different from the behaviour predicted by the analysis. Regarding Reactor Unit 2, on page IV-56 of Ref. [2](#) it is said that (while the RCIC was operating) “*reactor pressure was controlled by closing and opening of the SRV*”. In relation to Reactor Unit 3, in Table IV-5-3 of Ref. [2](#) it is stated that SRV repeatedly opened and closed from 14:52 local time onwards. Therefore, from the information we have to date, it is inferred that the SRVs complied with their “safety-valve function” as designed.

252 Finally, it should be mentioned that for reactors of the same type as the Fukushima-1 reactors, the situation in which there is total loss of AC-power supplies, and loss of the passive and semi-passive systems (discussed below) would be dealt with by rapid RPV depressurisation and injection of water to the vessel using alternative means (e.g. by using diesel-driven fire protection pumps). The RPV depressurisation would be achieved by opening the SRVs manually using pneumatic pressure (e.g. from nitrogen accumulators) and power from portable batteries (which would need dedicated or makeshift points for connection of portable equipment). In this regard, relevant information from the timeline of events at the Fukushima-1 reactors is as follows:

- As stated in the Section “[Timeline of Key Events](#)”, fresh water was injected into Reactor Unit 1 RPV via a core spray line using a fire pump from 05:46 local time on 12 March 2011. Presumably, actuations to depressurise the reactor would have been undertaken first, unless the RPV was already damaged and depressurised. Figure 3.1.2 in Attachment IV-1 of Ref. [2](#) shows low RPV pressure (measured) before start-up of water injection into the RPV. The same figure shows TEPCO’s analysis predicting RPV damage and depressurisation at approximately the same time as the start-up of water injection into the RPV. This may explain why there is no information regarding any attempt of the operators to use the SRVs to depressurise the reactor vessel. Another explanation would be if an SRV had seized open (after cycling for several hours and having been subject to sustained high temperatures) and had depressurised the RPV. The low RPV pressure and high drywell pressure values recorded approximately 11 hours after the earthquake (as shown in Figures 3.1.2 and 3.1.3 in Attachment IV-1 of Ref. [2](#)) may be indicative signs of the occurrence of such a scenario.
- The Section “[Timeline of Key Events](#)” detailed the efforts made at Reactor Unit 2 from 16:34 local time on 14 March 2011 to depressurise the RPV using an SRV prior to injecting sea water using fire pumps. Later, problems were encountered to maintain air pressure and power supply to the SRV (Table IV-5-2 of Ref. [2](#)). At 21:20 local time on the same day a second, apparently successful, attempt to depressurise the RPV was made using two SRVs. In the early hours of 15 March 2011, a third attempt to depressurise the RPV was made; it seems that, on this occasion, the depressurisation was not sufficient for the fire pumps to be able to inject sufficient water into the reactor.
- At Reactor Unit 3 reactor depressurisation using an SRV started at 09:08 local time on 13 March 2011 prior to injecting fresh borated water using fire pumps. Problems were also encountered at Reactor Unit 3 to maintain air pressure and power supply to the SRV (Table IV-5-3 of Ref. [2](#)).

Reactor Inventory Control and Emergency Core Cooling Systems

The Isolation Condenser

253 Under conditions of loss of off-site power and main steam isolation the Isolation Condenser was one of the systems in place to cool Fukushima-1 Reactor Unit 1 and maintain its water inventory. Fukushima-1 Reactor Unit 1 has two Isolation Condensers. A diagram of the system is shown in Figure IV-2-4 of Ref. [2](#). From Ref. [2](#) it is clear that following the Tohoku earthquake Fukushima-1 Reactor Unit 1 was initially cooled with the Isolation Condensers.

254 An 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 shut down and isolated from the turbine. The system is designed to start automatically upon receipt of a “high reactor pressure” signal sustained for a few seconds; it can also be activated manually by the operators.

- 255 Isolation Condensers operate by natural circulation (i.e. without pumps). During 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. These actuations require DC power supply that can be provided by batteries.
- 256 According to Ref. [8](#), which describes the general characteristics of the Isolation Condensers in BWR2/3 models, to obtain the required flow of condensate from the Isolation Condenser to the RPV, the operators could throttle the discharge valve from the control room. It is our understanding that implementation of the capability to throttle the Isolation Condenser discharge valve had been a modification from the original design for some BWRs. We do not know whether such capability existed at Fukushima-1 Reactor Unit 1.
- 257 During operation of the Isolation Condenser, 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 manually provided from various sources to fill-up the Isolation Condenser. According to Ref. [8](#), without adding more water an Isolation Condenser will empty, and its cooling capability will stop, in probably no more than 1.5 hours, although this time will of course depend on the size of the Isolation Condenser in each case.
- 258 It is believed that, as long as water could be provided to the shell side of the Isolation Condenser (e.g. with the diesel-driven fire protection pump), the Isolation Condenser would be capable of safely cooling the reactor core for a number of days without any other actuation, assuming there are no significant leaks from the primary circuit (some replenishment of water inventory may be necessary at some point to compensate for leaks through, for example, seals of the re-circulation pumps). According to Table IV-5-1 of Ref. [2](#) the TEPCO operators attempted to provide make-up water to the Isolation Condenser using a diesel-driven fire pump at 21:19 local time on 11 March 2011. However, from the development of the accidental sequence in this reactor, as discussed in [Annex L](#), it appears that the Isolation Condenser may have no longer been effective in keeping the reactor cooled.
- 259 It is clear that this passive system had an important role to play in cooling Reactor Unit 1 and its apparent early failure to adequately provide this function led to a significant escalation of the situation (core uncover, overheating and damage). The reasons for, and details of, this are still unclear. As described in the Section "[Timeline of Key Events](#)", prior to the tsunami and while there was still DC power available, the operators manually stopped both Isolation Condenser trains and manually started Train A in various occasions to control the reactor cooling rate at below 55°C/hr, as required by the operating procedures. We have not found information to explain why the operators did not, or could not, throttle the discharge valve to control the cooling rate. From the timing of events in Table IV-5-1 of Ref. [2](#) it is inferred that when DC power was lost because of the tsunami both Isolation Condenser trains were isolated and it was almost three hours later when the operators attempted to re-open Isolation Condenser Train A.

The High Pressure Coolant Injection System

- 260 Fukushima-1 Reactor Units 1, 2 and 3 were equipped with a semi-passive system called the High Pressure Coolant Injection (HPCI) system. A diagram of this system is shown in Figure IV-2-3 of Ref. [2](#).
- 261 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.

- 262 The HPCI requires DC power supply which can be provided by batteries. It does not require AC power, instrument air, or external cooling to perform its function.
- 263 The HPCI consists of a turbine driven two-stage pump (booster pump and main pump), auxiliary systems required for turbine operation, and associated piping and instrumentation. The HPCI turbine requires lubrication which is provided by a DC-powered oil pump. This pump is only required to operate at the start-up of the HPCI. After that, the HPCI pump itself provides the required oil pressure.
- 264 The HPCI is designed to start automatically on receipt of a “very low water level in the reactor” signal (also referred to as “low-low level” or “low-2 level”), 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 chamber.
- 265 This system is normally aligned to suction water from the Condensate Storage Tank (CST), the suppression pool being an alternative source of water with automatic realignment on “high suppression pool water level” or “low condensate storage tank water level”. Details about the exact capacity of the CSTs at the Fukushima-1 reactor units have not been found readily available.
- 266 On page 10 of the executive summary of Ref. [2](#) it is stated in relation to Fukushima-1 Reactor Unit 1: *“For at least one hour after the earthquake, the water level in the reactor was not low enough to trigger an automatic start-up (L-L: 148cm below the bottom of the separator) of the High Pressure Coolant Injection system (HPCI), and there has been no record of a start-up”*. This seems to confirm that the HPCI pump never started. We also understand that the RPV level behaviour at Fukushima-1 Reactor Unit 1 after the earthquake was consistent with the results of the transient analyses for loss of off-site power for this reactor type. So it appears that by the time that the “very low water level in the reactor vessel” was reached, sometime after the tsunami struck (due to loss of inventory through the SRVs, after cooling with the Isolation Condensers had stopped), DC power had already been lost and the HPCI could not start and inject water into Reactor Unit 1.
- 267 Looking at the new information available to us since we published the Interim Report, we still have not been able to establish whether Reactor Unit 2 HPCI was operable at all at any time. Reactor Unit-2 HPCI is only mentioned in Table 1-2 of Attachment IV-3 of Ref. [2](#), where it is indicated that the system function was lost due to the loss of power supply (auxiliary oil pump) after the tsunami.
- 268 According to Ref. [2](#) at Fukushima-1 Reactor Unit 3 the HPCI system started injecting into the RPV automatically, 21 hours after the earthquake, when “low-2 water level” in the RPV was reached. This happened approximately one hour after the RCIC system had tripped. It seems that the HPCI was running for approximately 14 hours. The reason why the HPCI stopped is thought to have been low reactor pressure (Ref. [2](#) page IV-73). It has been reported that Reactor Unit 3 RPV pressure dropped while the HPCI was operating, which has raised suggestions that Reactor Unit 3 HPCI could have had a steam leak but this has not been confirmed (Ref. [2](#) pages IV-74 and 76, and page 48 and Figure 3.3.1.10 of Attachment IV-1). In any case, the length of time that both the RCIC and HPCI had been operating in Reactor Unit 3, presumably suctioning water from the suppression chamber eventually (although no information on the switchover from CST to suppression pool suction has been found for Reactor Unit 3 for either of these two systems) and returning it back via the SRVs, and without any means to cool this water, appears to be beyond expectations.

The Reactor Core Isolation Cooling System

- 269 Both Fukushima-1 Reactor Units 2 and 3 were equipped with a further semi-passive cooling system, the RCIC. From Ref. [2](#) it is clear that these systems operated in both reactors for a number of hours and played a key role after the Tohoku earthquake. A diagram of this system is shown in Figure IV-2-5 of Ref. [2](#).
- 270 The function of the RCIC system is to provide core-cooling make up water to the RPV 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. The RCIC turbine will also trip upon receipt of signals indicating certain RCIC malfunctions.
- 271 As with the HPCI, the RCIC system is normally aligned to suction from the Condensate Storage Tank (CST). An alternative source of water for this system is the suppression pool, which would be used if the water level in the CST was low or if the water level in the suppression chamber was too high. It is believed that the realignment from suppression pool suction to CST suction is automatic (at least in some BWR models).
- 272 The RCIC turbine is driven by steam produced in the reactor vessel, and exhausts to the suppression chamber under water. DC electrical supply is necessary for opening valves for system actuation. DC power is also necessary for the control of the turbine and the system flow.
- 273 In the Interim Report we said that the exact causes for the RCIC and HPCI eventually stopping in Reactor Units 2 and 3 were not yet known. However, it could have been 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. We also indicated that a report on station blackout in the USA states that: *“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. [28](#), Section 8.1). The same Ref. [28](#), 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.
- 274 At the time of writing the Interim Report we were wondering, and indicated so, whether the Fukushima-1 operators might have taken any actions to extend the operation time of the HPCI and RCIC pumps, which appeared to be surprisingly long (Ref. [29](#)). We have now studied in detail all the body of new information provided in Ref. [2](#) and are still puzzled about the performance of the RCIC at Reactor Units 2 and 3 and the HPCI at Reactor Unit 3; both systems seem to have operated and been effective in keeping the cores cooled for much longer than anticipated. At the time of writing this report we still do not know with certainty whether the operators adopted any specific strategy to prolong the operation of these systems. The performance of the RCIC is discussed in more detail in the following paragraphs.
- 275 At Fukushima-1 Reactor Unit 2 the RCIC was started manually by the operators at least three times after the earthquake and before the tsunami. Each time the system operated as planned and on the first two occasions the system tripped on high reactor level as designed. About 12 hours later, the operators were able to verify locally that the system was still operating. About an hour later the system was realigned from CST suction to suctioning water from the suppression chamber – Ref. [2](#) page IV-57 indicates that the operators realigned the RCIC as CST water level decreased, and in order to control the increase of water level in the suppression pool. We do not know, however, whether at this time the CST water was depleted. It appears that the system continued running for

many hours afterwards providing some effective cooling. Around 36 hours after the earthquake an increase in drywell pressure was observed which may indicate that the cooling capability of the RCIC was partially degraded – this is not surprising considering that the water in the suppression chamber was not being cooled. However, Reactor Unit 2 RCIC does appear to have continued operating much longer than expected, keeping the core covered, despite the limiting capacity restraints on batteries surviving the tsunami, without cooling of the water in the suppression pool and without any apparent means to control the temperature in the vicinity of the RCIC pump.

- 276 At Fukushima-1 Reactor Unit 3, the RCIC was started manually by the operators after the earthquake. The system operated as planned and then tripped on high reactor level as designed. About half an hour later the operators started it again. It appears that Reactor Unit 2 RCIC tripped approximately 20 hours after the earthquake. For this unit, there is no information regarding any attempt of the operators to realign the system from CST suction to suctioning water from the suppression chamber (or of automatic realignment, if that was possible at all). Again, Reactor Unit 3 RCIC seems to have operated for longer than anticipated and appears to have been effective in keeping the core covered (the HPCI started automatically on low water level approximately one hour after the RCIC stopped, from which it may be possible to infer that the RPV level had been adequate up to that point).

Low Pressure Emergency Core Cooling Systems

- 277 BWRs are equipped with a number of AC-powered low pressure Emergency Core Cooling Systems (ECCS). BWR-3s and BWR-4s typically have a Core Spray (CS) system and a Low Pressure Coolant Injection (LPCI) system which has a variety of cooling functions for the reactor, the suppression chamber and the containment. Specific details about the Fukushima-1 low pressure AC-powered cooling systems and their relevance in the progression of the accidental sequences are discussed briefly in the following paragraphs.
- 278 According to Table IV-2-1 and Figure IV-2-1 of Ref. [2](#), Fukushima-1 Reactor Unit 1 had an AC-powered CS system. This was a two train low pressure system. Each train had two pumps. It is believed that the suppression pool was the primary source of water for this system although it appears that it could be realigned to take suction from the CST. The CS system did not operate during the progression of the accident, however the CS piping was used to spray fresh water into the reactor directly onto the core, using fire pumps, from around 15 hours after the earthquake. No information has been found about the existence of any additional low pressure emergency injection system at Fukushima-1 Reactor Unit 1.
- 279 According to Table IV-2-1 and Figures IV-2-2, 9 and 16 of Ref. [2](#), Fukushima-1 Reactor Units 2 and 3 had the following AC-powered emergency core cooling systems:
- CS system: This was a two train low pressure system. Each train had one pump suctioning from the suppression pool. From Ref. [2](#) it is not clear whether this system could be realigned to other water sources. It is believed that the CS system did not operate or play any role during the progression of the accident at Reactor Units 2 and 3.

- LPCI system: The LPCI consists of two trains each with two pumps and one heat exchanger. This system has the following functions: 1) low pressure injection into the reactor (taking suction from the suppression pool and discharging into the RPV via the recirculation loops downstream of the recirculation pumps); 2) suppression pool cooling; 3) containment cooling (spray cooling of the drywell and suppression chamber). The RHR function of this system for normal post-trip cooling has been discussed in the Section "[Normal Post-trip Cooling](#)". The containment cooling modes of this system and actuation at Fukushima-1 Reactor Unit 2 are discussed further in the Section "[Containment Pressure and Temperature Control](#)". There is no indication that the RHR / LPCI pumps actuated at any time in any mode at Fukushima-1 Reactor Unit 3.

Alternative Water Injection Mechanisms

- 280 According to Refs [25](#) and [2](#), in 1992, Japan's Nuclear Safety Commission (NSC), 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 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. At Fukushima-1 Reactor Units 1, 2 and 3, the severe accident management measures implemented included, among others (Table IV-2-2 of Ref. [2](#)), provision of alternative RPV water injection mechanisms, alternative containment spray and hardened containment venting capabilities – the last two are discussed in the Section "[Containment Pressure and Temperature Control](#)".
- 281 Alternative means of coolant injection were implemented in order to be able to use existing systems such as the condensate make-up water systems and fire extinguishing systems, to inject coolant into the RPV. This was achieved by modifying the piping network so that water from those alternative systems could be injected into the reactor or sprayed over the reactor core via existing emergency core cooling systems piping lines. Diagrams of the alternative water injection facilities are shown in Figures IV-2-10 (Reactor Unit 1) and IV-2-11 (Reactor Units 2 and 3) of Ref. [2](#). In Reactor Unit 3 an additional modification was implemented to allow sea water injection into the RPV via the LPCI / RHR piping network, using the RHR sea water pumps (Figure IV-2-12 of Ref. [2](#)). Also, Figure IV-4-1 of Ref. [2](#) shows a "conceptual" diagram of how truck fire engines could be aligned to inject water into the alternative water-injection piping network.
- 282 On page IV-12 of Ref. [2](#) it is indicated that TEPCO had developed procedures for coolant injection using alternative lines during severe accidents. However, on page IV-134 of the same reference it is said that alternative water injection into the reactors using heavy machinery such as fire engines (trucks) had not been considered as part of the accident management strategies; in the Fukushima accident this strategy was adopted as an ad-hoc applicable operation, although it was not successful in all instances because the reactor pressures were higher than the pump discharge pressures.
- 283 At Fukushima-1 Reactor Unit 1 the alternative water injection network was used first to inject fresh water into the RPV using fire engines via the CS lines from approximately 15 hours after the earthquake, and later to inject sea water.
- 284 At Reactor Unit 2, SRV opening operations in order to use alternative water injection mechanisms started on 14 March 2011 approximately three hours after the operators had identified that the reactor cooling capabilities using the RCIC had been lost. Due to difficulties in depressurising the RPV, the sea water injection was not effective to keep the core covered for several hours.

- 285 At Fukushima-1 Reactor Unit 3 the alternative water injection network was used to inject borated water into the RPV using fire engines from approximately seven hours after the HPCI had stopped, and to inject sea water several hours later.
- 286 In several instances RPV injection using alternative means had to be suspended because of shortages of fuel or water.
- 287 While it is clear that the injection of water into the RPVs of Reactor Units 1, 2 and 3 using alternative means was not sufficient, or timely enough, to avoid core melt in any of the reactors, it would have doubtless contributed to cooling the already degraded cores, and stopping the situation in the three units from escalating further. It is noted that the operators had to use considerable efforts in exceptional environmental conditions to effect such cooling.

Containment Pressure and Temperature Control

Containment Vacuum Relief Mechanisms

- 288 In the Mark I containment of Fukushima-1 Reactor Units 1 to 3 there were vacuum relief mechanisms (vacuum breakers). These devices maintain the balance of the pressures between the drywell and the suppression chamber, protect the containment against low internal pressure and avoid collapse of the drywell (torus → drywell vacuum breakers) or of the torus (reactor building → torus vacuum breakers).
- The first of these systems (torus → drywell vacuum breakers) consists of a number of valves that vent the suppression chamber to the drywell when the pressure in the suppression chamber exceeds the pressure in the drywell by a pre-determined value. This system does not require any power supply.
 - The second vacuum relief system (reactor building → torus vacuum breakers) consists of two vacuum relief lines that vent air from the secondary containment to the suppression chamber when the pressure in the secondary containment exceeds the pressure in the suppression chamber by a pre-determined value.
- 289 We do not know whether the vacuum breakers opened and closed at some points during the progression of the sequences at Fukushima-1 Reactor Units 1 to 3. Also, we have not found any information leading us to believe that the vacuum breakers did not operate if / as required or that they might have contributed to degrading the situation during the accident.

Containment Cooling

- 290 Cooling of the suppression chamber 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, due to the discharge of steam from the RPV, if heat is not removed. This would cause an increase in the pressure of steam, leading to a steady increase in the containment pressure. Fukushima-1 Reactor Units 1 to 3 had systems to provide suppression pool and drywell cooling functions; these are discussed in the following paragraphs.
- 291 According to Table IV-2-1 and Figures IV-2-1 and IV-2-15 of Ref. [2](#), Fukushima-1 Reactor Unit 1 had a Containment Cooling System (CCS). This was a two train system; each train had two pumps and one heat exchanger. The CCS provided suppression pool cooling, spray of the torus and spray of the drywell. The heat exchangers were cooled by the sea water system. The CCS was started manually

approximately 20 minutes after the earthquake in its suppression chamber spray mode and presumably operated for around 30 minutes (while AC power was available from the emergency diesel generators).

- 292 As mentioned earlier, at Fukushima-1 Reactor Units 2 and 3, the suppression pool cooling function was provided by one of the operating modes of the AC-powered LPCI / RHR. In this mode, the heat in the suppression chamber is removed via the LPCI / 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 water from the suppression pool into the drywell or suppression chamber atmospheres to control primary containment pressure. Approximately 15 minutes after the earthquake, the operators at Fukushima-1 Reactor Unit 2 started the LPCI / RHR pumps in suppression pool cooling mode. The pumps stopped because their power supplies were lost due to the tsunami. The tsunami also damaged the sea water pumps cooling the heat exchangers. From that moment the capability of cooling the suppression pool and the drywell, other than by using alternative means, was lost. There is no indication that the RHR / LPCI pumps actuated at any time in any mode at Fukushima-1 Reactor Unit 3.

Alternative Containment Spray

- 293 According to page IV-13 of Ref. [2](#), at Fukushima-1 Reactor Units 1, 2 and 3, the severe accident management measures implemented included provision of alternative containment spray (drywell and suppression chamber), as shown in Figures IV-2-15 (Reactor Unit 1) and IV-2-16 (Reactor Units 2 and 3) of the same reference.
- 294 On 13 March 2011, approximately 40 hours after the earthquake, primary containment spraying operations started in Reactor Unit 3 using fire engines, presumably via the alternative containment spray piping network. Other than that, we have not found information regarding whether the alternative containment spray capabilities were used at the other reactor units at any time.
- 295 It should be noted that on page IV-136 of Ref. [2](#) it is stated that TEPCO implemented the capability of injecting water into the space under the RPV (pedestal) using the same piping as for the alternative spray. This would have provided the means to cool a molten core ejected from a failed RPV and accumulated on the floor of the drywell. Further discussions on the progression of the severe accident are provided in [Annex L](#).

Containment Venting

- 296 From the information reported and the discussion in the previous sub-sections, it is clear that the only effective solution available to relieve high pressure from the primary containments and preserve their integrity in Reactor Units 1 to 3, was to vent the containment vessels using the hardened containment vents.
- 297 At the time of writing the Interim Report, we knew that the TEPCO operators had conducted containment venting operations at the three reactor units, but we could not understand or explain the explosions in the reactor buildings that occurred after venting operations had been undertaken. At that time we did not have details about the means used to vent the containments or why the venting operations appeared to have been ineffective. We did appreciate, however, that this system was of key relevance regarding the progression of the accident sequences at the Fukushima-1 Reactor Units 1 to 3. Thus, in the Interim Report we provided information on the history of, and rationale for, the implementation of hardened containment venting facilities at the

BWRs with Mark I containments. Although we know more now, we still believe that the historical information is relevant and therefore we have kept it in this Final Report (next paragraph).

298 In September 1989, the United States Nuclear Regulatory Commission (US NRC) issued Generic Letter 89-16 (Ref. [30](#)) requesting all (US) holders of operating licences 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.

299 As discussed earlier, the severe accident management measures implemented at Fukushima-1 Reactor Units 1, 2 and 3 included provision of hardened containment venting capabilities, referred to as “Compressive Strengthening Vent” in Table IV-2-2 of Ref. [2](#). According to page IV-13 of the same reference, TEPCO had built vent pipes extending from the suppression chamber and the drywell to the stacks in their BWR Mark I NPPs from 1999 to 2001. These vent lines had been constructed with strengthened pressure resistance.

300 Therefore, at each of Fukushima-1 Reactor Units 1 to 3, both the drywell and the torus could be vented via the hardened vent lines. Suppression chamber venting (wet venting) would in general take priority because the water in the suppression pool would provide a filtering effect and fission product retention. In order to vent the containment through the torus or through the drywell venting lines a Motor Operated Valve (MOV) and an Air Operated Valve (AOV) needed to be opened. The MOVs required AC power to open. The AOVs required both power supply and air pressure to open. The venting lines had rupture disks to prevent inadvertent operations. Diagrams of the containment venting facilities are shown in Figures IV-2-13 (Reactor Unit 1) and IV-2-14 (Reactor Units 2 and 3) of Ref. [2](#).

301 For BWRs with Mark I containments, containment venting operations are required by the severe accident management procedures when a certain value of pressure in the containment is reached. On page IV-13 of Ref. [2](#) it is stated that (for the TEPCO facilities):

“The procedures for operation in severe accident define the PCV (primary containment vessel) vent conditions and the PCV vent operation during severe accidents as follows: PVC vent from the S/C (suppression chamber) (hereinafter referred to as wet-vent) shall be given priority; and when the PCV pressure reaches the maximum operating pressure before core damage, when the pressure is expected to reach about twice as high as the maximum operating pressure and if RHR is not expected to be recovered, wet vent shall be conducted if the total coolant injection from the external water source is equal to or less than the submergence level of the vent line in the S/C or PCV vent from the D/W (drywell) (hereinafter referred to as “dry vent”) shall be conducted if the vent line of the S/C is submerged”.

According to the same procedures, the need for venting after core degradation has started would be determined by the chief of the emergency response headquarters. It appears though that the Japanese government had to authorise these operations, presumably because during containment venting after core damage has occurred, a certain amount of radioactivity would be released to the environment. However, there is also information that action was taken on-site to alleviate the position, when appropriate.

- 302 The pressure in the Fukushima-1 Reactor Unit 1 containment reached high values approximately ten hours after the earthquake and continued increasing during the next hour or so. TEPCO operators started preparation for wet containment venting some time later. Since there was no power supply or C&I, the valve alignment had to be done locally, where there were already high radiation fields, which hindered the operations significantly. Only 18 hours after the earthquake the operators managed to open the MOV, but only partially. To open the AOV, the operators had to use a temporary compressor to provide the required air pressure. Finally, reduction of containment pressure was successful, but only almost 24 hours after the earthquake.
- 303 According to page IV-58 of Ref. [2](#), it appears that at 06:50 local time on 12 March 2011 (approximately 16 hours after the earthquake) Japan's Minister of Economy, Trade and Industry, ordered TEPCO to carry out operations to vent the Fukushima-1 Reactor Unit 2 containment to reduce pressure. Configuration for wet venting was carried out, more than a day later, while the RCIC was still operating. Dry venting was attempted more than a day and a half after the first venting operation but pressure reduction could not be verified.
- 304 At Fukushima-1 Reactor Unit 3, wet containment venting started a few hours after the HPCI had stopped. The AOV in the venting line later closed due to loss of air pressure. Later it appears that the AOV was opened again several times to carry out wet venting operations.
- 305 Figure 3.1.3 of Attachment 1 of Ref. [2](#) shows that Fukushima-1 Reactor Unit 1 containment pressures reached values above 0.8MPa (exceeding the maximum working pressure, 0.426MPag). On page IV-47 of the same report it is implied that the high pressures and temperatures would have weakened penetration seals and the gasket on the flange section of the drywell creating leak paths. Indeed, a small reduction in Reactor Unit 1 containment pressure before containment venting started was reported. A similar discussion for Reactor Unit 3 is provided on page IV-79. The occurrence of leaks from seals and gaskets could have been the reason for the release and accumulation of hydrogen in the top floors of the reactor buildings in Reactor Units 1 and 3. Similarly, in Reactor Unit 2 it is possible that hydrogen leaked from the suppression chamber (e.g. via damaged bellows or flanges) and exploded in the torus room (page IV-64 of Ref. [2](#)). It should be noted that the hydrogen gas might have found its way to the points of accumulation in the reactor buildings in Reactor Units 1, 2 and 3 via other routes, but no additional or specific information in this regard has been found in Ref. [2](#). In any case, the pressure increases in the three primary containments to the point of opening leak paths, as suggested in Ref. [2](#), may indicate that containment venting operations had not been effective (or timely) enough to preserve the integrity of the primary containments.
- 306 For completeness, it is worth mentioning that on 15 March 2011 at 06:00 local time an explosion assumed to be a hydrogen explosion occurred in the upper part of the Unit 4 reactor building causing considerable damage. The current view is that the accumulation of hydrogen inside the Unit 4 reactor building was caused by backflow from Reactor Unit 3 containment venting discharge line to the ventilation stack into Reactor Unit 4 via its standby gas treatment system discharge line, as both lines are connected (Ref. [2](#), pages IV-91 and IV-97).

Hydrogen Control

- 307 During the progression of the accidental sequences, when the cooling of the reactor core has stopped and the temperatures of the core increase above 1000°C, the zirconium in the alloy of the nuclear fuel claddings reacts with the steam and oxidizes, and hydrogen gas is released. Hydrogen explosions can happen if sufficient hydrogen and oxygen are present.
- 308 This is a well-known phenomenon and BWRs have been designed cognisant of such scenarios. In the Mark I containment design, 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. No instances of hydrogen combustion inside the primary containments of Fukushima-1 Reactor Units 1 and 3 have been reported and, therefore, there is no reason to believe that the containments did not remain inert while hydrogen was being produced due to oxidation of the fuel cladding, or from radiolysis of the water steam. The same comment applies to Reactor Unit 2 providing the hydrogen explosion had occurred outside the suppression chamber, as currently believed.
- 309 According to information provided in several places in Ref. [2](#), it appears that the Fukushima-1 reactor units had an additional system in place to prevent hydrogen combustion inside the primary containment called Flammability Control System (FCS). No details regarding the design of this system have been found but it is believed that the FCSs were not available in any of Fukushima-1 Reactor Units 1 to 3 because their operation required power supplies which had been lost (Ref. [2](#) page IV-135).
- 310 In the recovery phase days after the accident, TEPCO's strategy was to resume the active injection of nitrogen where possible into the containments to minimise the risks of further explosions.

Spent Fuel Pond Factors During the Fukushima Accident

- 311 There were three main challenges to the safe storage of spent fuel at Fukushima-1:
- Structural damage to the reactor ponds and containment.
 - The loss of pond water cooling and top up capability.
 - Damage to fuel due to violent shaking from the earthquake and subsequent debris falling onto the fuel. The initial geometry and spatial arrangement of the fuel in the storage racks could also have been altered during the earthquake, eroding margins to criticality.
- 312 The spent fuel pool storage ponds in the reactor buildings are massive concrete and steel structures, designed and assessed to withstand seismic events. As shown in [Table 4](#), the observed horizontal accelerations were broadly similar or slightly in excess of the functionality values, and the vertical accelerations were less than the functionality values. The loads are therefore believed to have remained within the capability of the structures. As a result, it appears that the ponds retained their integrity and ability to maintain a water level above the fuel. The explosions in Reactor Units 1 to 4 were additional threats, but again the ponds seem to have maintained their function to keep the fuel covered with water. In the recovery phase, TEPCO have worked to provide additional support to the structure of Reactor Unit 4's pond but this appears to be precautionary against further seismic activity.

- 313 The combined effects of a loss of AC power on-site and sea water pumps meant that all ponds on-site lost active cooling (including Reactor Units 5 and 6, and the common pond). Without cooling, water temperatures rose, evaporation rates increased and, if allowed to continue, pool boiling would have occurred, increasing the rate of water inventory loss. Therefore it was necessary to provide make-up water to compensate for the water loss, despite the evidence that the structure of the ponds appears to have retained integrity.
- 314 It took over a week to provide make-up water to Reactor Unit 5 and Unit 6 ponds (and the common pond). However while the water temperatures were elevated above the normal operational levels, the rises were relatively modest, and once power and a cooling function had been re-established (via temporary sea water pumps), the temperatures rapidly dropped to stable levels.
- 315 There was a perceived greater threat and urgency with respect to providing make-up water to Reactor Units 1 to 4, especially given the evident damage the buildings of Reactor Units 3 and 4 and the higher decay heat levels in Reactor Unit 4's pond. The access to the spent fuel ponds and their height above the ground level were challenges to be overcome. The helicopter drops were rapidly discontinued as ineffective. The water cannon from the ground was probably not very efficient but given that in hindsight the ponds had not suffered significant structural damage it may have been adequate. The concrete pumping trucks (initially just one) with their articulated arms seem to have been invaluable in getting large quantities of water to the ponds until more direct means of providing make-up water were established. Several weeks after the initial earthquake, to reach a sustainable stable state, active cooling has to be re-established. However it is only at the time of writing, several months later, that this is being established.
- 316 Therefore, as stated in the Section "[Timeline of Key Events](#)" it appears that the (considerable) efforts to add water to the ponds were effective in keeping the fuel covered. However, this was not known during the initial phases of the accident, especially to international observers. Fuel uncovering seemed a very real possibility / likelihood given the damage to the reactor buildings and the initial assumption of a hydrogen explosion in Reactor Unit 4 (which had no fuel in the reactor). This led to a concern about zirconium fires which would significantly increase the rate of release and mobilisation of radioactivity from the ponds, with effectively no barriers against release of radioactivity.
- 317 The possibility of zirconium fires was discussed within ONR and with other nuclear regulators around the world. It was established that there does not appear to be a general consensus on the plant conditions required to cause ignition, or the amount of cooling time that the spent fuel requires to eliminate the possibility of its zirconium cladding igniting. Therefore, there was a great deal of uncertainty about whether zirconium fires were a likely outcome.
- 318 Cooling time is not the only factor in the propensity for uncovered zirconium-clad fuel to ignite. The configuration of a fuel assembly relative to its neighbours will affect the efficiency of heat transfer, as will any debris in the pool. Given that there are so many variables and uncertainties in the local conditions in the individual ponds, and the relatively limited amount of research in ideal test conditions, it is still probably impossible to say definitively if there would have been a zirconium fire in any of the ponds if the fuel had become uncovered. This is an area where further research may be warranted.
- 319 What appears clear is that by maintaining the structural integrity of the ponds and providing make-up, a zirconium fire could not occur. As a result, despite the earthquake, tsunami, subsequent loss of active cooling and the local explosions, the fuel in the ponds has not been a significant contributor to the realised consequences of the accident. Further research and accident analysis is needed to establish if there was ever a risk of a zirconium fire under the conditions experienced. Even if it is not

possible to reduce significantly the uncertainty in predictions of zirconium ignition, it should be possible to show that some racking arrangements are less susceptible than others and may represent good practice in the future. However a reliance on racking arrangements should be a long way down the hierarchy of measures taken to protect the fuel, with keeping fuel covered by water (even boiling water) being demonstrably more effective.

- 320 There is no strong evidence of significant fuel damage from shaking or debris falling on the fuel. Visual inspections of ponds do not show any apparent damage in Reactor Unit 4, although examination will not be complete at this time. It is impossible to tell the state of the fuel beneath the debris in Reactor Unit 3. Water samples from the ponds reported in Ref. [1](#) have been interpreted as not indicative of significant fuel damage, although drawing conclusions from raised caesium activity levels (which would be indicative of fuel failures) is difficult because raised levels are inevitable throughout the Fukushima site (including the ponds) as a result of the damage to the reactors.
- 321 There is no evidence to suggest any criticality events occurred in the ponds.
- 322 It is possible that the seismic ground motion caused a significant amount of sloshing in the ponds, with the potential for water inventory to be lost. This would increase the urgency for the provision of additional make-up water. ONR has no knowledge if this occurred to any significant extent and, with the loss of instrumentation, lighting and access for personnel in the period following the accident, more detailed information is not expected. This is something that can be engineered for even if it was a phenomena that occurred to any extent (e.g. by having an adequate height between the water level and the operating deck, have drains which return water to the pond, ability to provide additional make-up water).
- 323 During normal operation, the chemistry of a fuel pond is controlled. Control of the chemistry would have been lost when the sea water was used to provide make-up water. Given the seriousness of the situation, the lack of fresh water supplies and the overriding requirement to keep the fuel covered, this was the appropriate action to take. The presence of salt 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. At some point in the future during the recovery phase, special consideration may need to be given to the handling and storage of the fuel compared to fuel which has always experienced controlled conditions. However this can be planned and engineered for in a controlled manner, and is a price worth paying given that a significant escalation of the Fukushima accident was possibly avoided.
- 324 In summary, by having a pond structure that could maintain its integrity at a limiting design basis seismic event, decay heat loadings in the ponds which led to relatively limited water temperature rises despite a lack of active cooling, and the ability to provide make-up water for a prolonged period of time (admittedly by unconventional means and with access enabled by damage to the buildings), the ponds appear not to have been significant contributor to the consequences of the accident. There are still lessons to be learnt that may represent good practice for the future in pond design and operation.
- 325 The response to the Interim Report recommendations and the European Council “Stress Tests” being carried out in the UK should demonstrate whether the UK spent fuel ponds are passively “safe” by design, and in some cases whether it is ALARP to impose relatively straight forward minimum cooling times or racking configurations to ensure that with a total loss of active cooling (possibly even a catastrophic loss of water inventory) the fuel should remain substantially intact.

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

Seismic Design

- 326 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.
- 327 Reactor Unit 1 was originally designed against seismic loading by the reactor supplier General Electric, via a subcontract to the company URS John Blume. The original design basis for Reactor Units 1 to 5 is between 0.25g and 0.3g peak ground acceleration and 0.5g pga for Reactor Unit 6. (Ref. [2](#)). 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. [31](#)) was first published in 1970. There is a Japanese regulatory guide for reviewing nuclear reactor site evaluation and application criteria which was originally issued in 1964 and updated in 1989 (Ref. [32](#)). This guide discusses demographic criteria rather than siting with respect to external hazards.
- 328 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. [33](#)). Detailed technical guidance is contained in JEAG 4601 (Ref. [31](#)). These approaches were updated in 2006, and the following statement was provided in the Japanese submission to the CNS in 2007 (Ref. [34](#)).
- “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.”*
- 329 The approach in the most recent version of JEAG 4601 (Ref. [31](#)) 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.
- 330 We have not seen the detailed response referred to in Japan’s 2007 submission to the Convention on Nuclear Safety (Ref. [34](#)), however TEPCO provided a short press briefing (Ref. [16](#)), which gave some indication of the basic earthquake ground motion S_s for the Fukushima-1 plant according to the guidelines in Ref. [34](#). In addition, they provided the measured levels of acceleration in the basements of all of the units at the Fukushima-1 site. [Table 4](#) 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

- 331 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.
- 332 A detailed review of the approach to defining the seismic hazard has not been possible to date. It appears from a review of Ref. 33 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.
- 333 It is well known that there have been significant events in the same subduction zone in 869 (M_w 8.6) 1611 (M_w 8.5), 1896 (M_w 7.6) and 1933 (M_w 8.6) accompanied by large tsunamis. The development of such a large event as Tohoku involving the rupture along such a long segment of the source fault was not considered credible by Japanese experts. The values of S_s appear to have been based on the assumption of an event of M_j 7.9 located in relatively close proximity to the plant. This gives rise to the values shown in Table 4. The hazard derivation for Fukushima clearly underestimated the levels of ground motion that are possible. It is considered that there was a lack of conservative decision making within the hazard evaluation.

Design Against Flooding

- 334 It has not been possible to identify the regulatory requirements in Japan for carrying out flood risk assessments. The original estimate of tsunami risk for the site undertaken during the construction period (1966 to 1972) was based on assumptions around a scenario of the Chile Earthquake of 1964 propagating a tsunami across the Pacific. This resulted in a design level of OP +3.122m. This remains the regulatory approved basis.
- 335 It is understood however that the tsunami risk is currently addressed using a publication by the Japanese Society for Civil Engineers (Ref. 35). 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

^{††} The location at which S_s is determined appears from Ref. 31 to be at a rock level referred to as “free surface of the base stratum”. This is assumed to be at the foundation to rock interface but assumes no effects from soil-structure interaction.

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. [35](#).

- 336 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 re-evaluated as OP +5.7m. This was based on a scenario around an event of M_w 7.9 (based on the 1938 offshore Shioyazaki Earthquake) 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.
- 337 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. [35](#) 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 20m maximum height.
- 338 Research into the 869 (Jogon) event suggests that the ensuing tsunami spread up to 4km inland and had coastal heights of 8m (excluding run-up) (Ref. [36](#)). In addition, there is evidence for a further two similar events in the previous 3000 years. It is therefore clear from a simple review of historical data that an event significantly bigger than the design event could be reasonably foreseen with a relatively high frequency. This is a major failing in the design basis, as commented on by the IAEA fact-finding mission (Re. [3](#)).

Factors Relating to the Local Grid System

- 339 The six reactors on the Fukushima-1 site were either receiving electrical power or transmitting electrical power from six overhead transmission lines connected to the local grid network. Four of the six transmission lines were connected to Shin Fukushima electricity substation located approximately 8km from the site.
- 340 Immediately following the earthquake the three generating units tripped off and the station power supply was switched to the off-site power supply. However, the earthquake caused damage to circuit breakers, cables and the collapse of transmission towers resulting in the loss of all external electrical power supplies to the site. Therefore, the emergency diesel generators for each unit automatically started and proceeded to provide electrical power for maintaining the function for cooling the reactors and spent fuel pools.
- 341 Safety functions for all six units were maintained until the tsunami hit the site and as a consequence all the emergency diesel generator diesel fuel tanks, except one for Reactor Unit 6, ceased operating because sea water cooling systems for diesel generators and metal-clad switchgear were submerged; this resulted in the loss of AC power to Reactor Units 1 to 5.

- 342 The complete loss of grid derived electrical power, significant reduction in on-site standby power generation and effects of the Tsunami on electrical components and infrastructure resulted in the prolonged loss of engineered safeguard functionality.

Key On-site Factors Relating to Electrical Systems

- 343 Details of the design of safety-related electrical provisions serving the six nuclear power plants at the Fukushima-1 site are 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.
- 344 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.
- 345 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.
- 346 The initial seismic event disrupted electrical power supplies from the grid, resulted in a reactor trip and initiation of emergency diesel generator operation. The emergency supplies systems appeared to have provided electrical power for essential safety functions until rendered inoperable by the tsunami. Inoperability of the diesel generators was because of flooding effects on the diesel engine cooling systems, damage to switchgear and diesel fuel tanks.
- 347 The total extent of damage to the site electrical systems is not yet known in detail, although there is some information that some percentage of the system was inoperative. However, photographic evidence suggests that the site and off-site infrastructures were severely damaged; initial investigations confirm the damage to electrical switchboards and other electrical components sustained from the tsunami.
- 348 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 was 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.

Key On-site Factors Relating to Control and Instrumentation Systems

- 349 Immediately following an earthquake the C&I safety systems shut down the operational reactors safely and initiate post-trip cooling, and there are no reports of C&I equipment failure. However, the loss of the electrical power which occurred following the tsunami rendered most of the C&I equipment inoperable. In particular, there are reports that the safety parameter display system was not functional, such that plant status could not be determined.

- 350 In normal operation station staff are able to control and monitor the plant remotely from the Main Control Rooms, but due to the loss of electrical power many of the control room facilities were not available on Units 1 to 4 and access to control rooms was also restricted due to environmental factors. Limited control and monitoring facilities were established by using ad hoc techniques such as:
- the use of portable electrical power sources, such as car batteries, to provide power to C&I components;
 - the use of portable compressors to drive pneumatically operated control equipment;
 - manual operation of what would normally be electrically driven control equipment; and
 - some C&I monitoring equipment did not require electrical power to operate, and therefore it was possible to take readings of plant parameter values locally.
- 351 By using such techniques station staff were able to monitor some selection of plant parameters and to perform some limited key mitigating actions, such as PCV venting. However, these techniques are time consuming and laborious even under normal conditions, and during this event there were additional adverse factors such as poor lighting and restricted access to plant areas due to high radiation levels. A detailed description of the actions taken by operators is provided in the Section "[Fukushima-1 Operator Actions](#)".
- 352 A number of problems or suspected problems with instrumentation were reported which appear to be connected with severe accident conditions, e.g. RPV level measurements were believed to be reading high, and some instruments were not able to measure parameters as values were out of range, e.g. dry well temperature. These problems created uncertainty with respect to the actual status of plant. There may have been other failures or potential problems with C&I equipment resulting from the effects of this event which were not revealed due to the restricted availability of on-site electrical power, and there is as yet insufficient information available to determine the potential extent and significance of such unrevealed failures.
- 353 The reductions in C&I capability experienced during this event had a significant impact. In particular, there was a detrimental effect with respect to the following aspects of event management:
- the availability of automatic C&I safety functions;
 - the ability of station staff to make decisions about the best means of mitigating risk due to the lack of plant status information and uncertainty with respect to the accuracy of information that was available;
 - the ability of the station staff to effect timely mitigating actions (such as PCV venting); and
 - the ability of station staff to determine the effectiveness of mitigation actions.
- 354 The effectiveness of the retrospective analysis of the event has also been impacted due to the unavailability of data from C&I equipment which would normally log operator actions and the status of plant variables in real time.

Key On-site Factors Relating to Operator Actions

- 355 Since the publication of the Interim Report (Ref. [1](#)), considerably more information has become available on the operator actions and overall severe accident management strategies employed at Fukushima-1. This has allowed us to gain a better overall understanding of the challenges facing

the operators, and the overall response. However much of the detail of the detailed decision making processes, operator actions and co-ordination between the various parties involved (including NISA and TEPCO staff, and government ministers) in the response are still emerging and not fully known by ONR at this time, although they appear to have influenced the timing of some of the response actions. Consequently this section presents ONR's current understanding of the operator actions and we will continue to review new information as it becomes available.

- 356 The Section "[Timeline of Key Events](#)" presents a detailed timeline of the key events at Fukushima-1 for Reactor Units 1 to 6 and spent fuel ponds; this includes the operator actions undertaken. The Section "[Role and Relevance of Key Reactor Systems During the Fukushima Accident](#)" presents the role and relevance of key reactor systems during the Fukushima accident. This allows the detailed operator actions described in the timeline to be understood in relation to the key safety functions they contribute to, and on the potential options that may have been available to the operators at key points during the accident. The following summaries present an overview of the emergency and severe accident management strategies that appear to have been employed in response to the unfolding scenarios based on this technical information. The tables in [Annex K](#) provides a concise summary of the key events, actions and strategies employed for each reactor unit and for the spent fuel and common ponds of Fukushima-1.

Fukushima-1 Operator Actions

- 357 The earthquake at 14:46 local time on 11 March 2011 led to the operating reactors shutting down as designed and on-site diesel generators started as required when the loss of off-site power occurred due to the earthquake impact. The operators responded in accordance with procedures in ensuring shut down and cooling via the appropriate systems for each reactor. This essentially presented a design basis accident that was within the scope of Emergency Operating Procedures (EOP) and the operators training should have prepared them for. It was the impact of the tsunami that then severely exacerbated the situation with differing impacts across the reactor units and spent fuel ponds.

Reactor Unit 1

- 358 Prior to the tsunami Reactor Unit 1 was being cooled by intermittent operation of the relevant back-up system for a loss of AC power, namely the Isolation Condenser. Instrumentation and control of essential equipment was available, powered by the DC battery back system.
- 359 The tsunami hit at 15:37 local time and led to:
- Failure of the Isolation Condenser cooling system (due to MOVs being closed at the time of the impact; DC power was needed to re-open them); and failure of the ultimate heat sink due to loss of the sea-water pumps.
 - Loss of all instrumentation.
 - Extensive flooding and damage across the site - making local plant conditions generally very difficult and hazardous.
 - Loss of lighting to the unit control room.
 - Very limited communication systems on-site and off-site (only 1 wired phone between the control room and On-site Emergency Control Centre (OECC)).

- Evacuation of workers initially.

- 360 At this point the operators' immediate priorities were to re-establish essential instrumentation and derive key parameter information, re-establish reactor core cooling via the Isolation Condenser system, and to re-establish lighting to the control room. The operators were successful in all of these objectives in the first few hours following the event, although maintaining Isolation Condenser cooling was problematic and required continual actions during 11 March 2011. Restoration of these functions had required considerable improvisation involving attempts at manual valve opening, using car batteries to power instrumentation and using a diesel driven fire pump to supply water to the body of the Isolation Condenser.
- 361 By the early hours of 12 March 2011 TEPCO suspected PCV pressures may have exceeded their maximum permitted pressure and informed NISA. Around the same time the cooling via the Isolation Condenser system failed. The operators then resorted to injecting fresh water via the core spray lines using fire pumps.
- 362 At 06:50 local time on the morning of the 12 March 2011 the Minister of Economy, Trade and Industry ordered TEPCO to reduce pressure in the PCV for Reactor Units 1 and 2. The operators made various attempts for containment venting and eventually succeeded by improvising valve actuation using a temporary air compressor and AC generator at around 14:00 local time on 12 March 2011.
- 363 At 14:53 local time on 12 March 2011 fresh water injection via the core spray lines ceased due to exhaustion of the fresh water supplies. At 15:36 local time there was a hydrogen explosion. At 17:55 local time the Minister ordered TEPCO to inject sea-water into the reactor to maintain core cooling. The operators successfully commenced sea-water injection using the fire fighting lines at 19:04 local time that day. It appears that no RPV depressurisation was required to enable this sea-water injection; it is believed that the RPV had depressurised sufficiently due to damage. Sea-water injection was effectively continued until 25 March 2011 when it was changed over to freshwater injection and recovery actions continued.
- 364 The overall response strategy for Reactor Unit 1 can be summarised as:
- Initially cooling using the Isolation Condenser.
 - Then resorting to reactor cooling via alternative water injection into reactor via alternative means (fire fighting lines) - no need to depressurise to permit injection as RPV depressurised (assumed due to damage).
 - PCV pressure reduction (via containment venting).
 - Sea-water injection.
- 365 Additionally considerable improvisation was required to obtain plant status data, and to restore essential plant information and control of required plant items.

Reactor Unit 2

- 366 The situation for Reactor Unit 2 was initially very similar to that for Reactor Unit 1 though with reactor cooling being provided by the RCIC system. When the tsunami struck at 15:37 local time the impact was very similar to that for Reactor Unit 1, although very limited functionality was still available from DC backed-systems. The RCIC system continued to operate for some days with RPV injection using the turbine driven pumps and steam being dumped into the suppression chambers causing the PCV pressure and temperature to rise progressively.

- 367 The operators' immediate priorities were similar to that for Reactor Unit 1, with the main requirements being to re-establish essential instrumentation and derive key parameter information, ensure continued reactor core cooling via the RCIC system, and to re-establish lighting to the control room. The operators were successful in all of these objectives in the first few hours following the event obtaining observations of the reactor water levels at 22:00 local time on 11 March 2011. This confirmed that the RCIC operation was maintaining a steady level. In the early hours of 12 March 2011 the operators switched water sources for the RCIC from the condensate storage tank to the S/C in response to the increase in S/C level and depleting CST level.
- 368 On 14 March 2011 at 11:30 local time the operators noted that the water level started to drop and by 13:25 local time judged the RCIC to be inoperable and consequently they informed NISA of a loss of reactor coolant function. At 12 noon local time the operators had started making preparations for sea-water injection when the reactor level was decreasing but also attempted to re-establish RCIC operation. As this failed, RPV pressure reduction and sea-water injection commenced at 16:34 local time using a fire pump. RPV pressure reduction required the operators to use a car battery as a DC power source to open an SRV. In subsequent hours the operators had to connect a nitrogen cylinder to maintain SRV operation; and to commission a second fire pump to restore sea-water injection following failure of the first pump. Sea-water injection into the RPV effectively continued until 26 March 2011 when a change-over to freshwater injection started.
- 369 On 13 March 2011 operators had undertaken containment wet venting operations at 11:00 local time in response to the Minister's order to reduce PCV pressures in Reactor Units 1 and 2 at 06:50 local time earlier that morning. This had required improvisation using an air cylinder to open an AOV and an engine generator to provide AC power to open another valve.
- 370 The overall response strategy for Reactor Unit 2 can be summarised as:
- Cooling initially by RCIC - managing appropriate waters supplies.
 - PCV pressure relief.
 - Then RPV pressure reduction and sea-water injection on RCIC failure.
 - As for Reactor Unit 1, considerable improvisation was required to re-establish control of key plant items and to obtain parameter information.

Reactor Unit 3

- 371 The earthquake led to a loss of AC power and manual start-up of the RCIC following procedures. The tsunami had slightly less impact initially on Reactor Unit 3 than on Reactor Units 1 and 2 in that back-up batteries provided DC power to some key equipment and instrumentation for up to 30 hours after the tsunami. At the moment the tsunami hit the RCIC was not operating having tripped on high water level.
- 372 The operators' initial responses were similar to that for Reactor Units 1 and 2. The RCIC was manually re-started around 30 minutes after the tsunami - as DC power was available no improvised means of operation was necessary. The RCIC continued providing reactor cooling until 11:36 local time the next morning (12 March 2011). The HPIC (essentially the next back-up cooling system) started automatically around 1 hour later (at 12:35 local time) and continued operating until the early hours of the 13 March 2011. The operators observed the water levels in the RPV and determined that the level had dropped to potentially leave parts of the core uncovered. At 05:10 local time they attempted to inject water via the RCIC but this was unsuccessful.

- 373 Following failure of the RCIC and HPCI the operators then shifted to depressurising the RPV to permit water injection via alternative systems and depressurising the PCV. The operators were able to open vent valves using similar approaches as on Reactor Units 1 and 2 using engine driven air compressors, generators and air cylinders. Borated water was initially injected into the RPV via the fire system lines. In the early afternoon of 13 March 2011 sea-water injection commenced using diesel driven fire pumps. In the following days, sea-water injection continued until 25 March 2011 when a switch to fresh water injection was made. The operators had to identify and respond to failure of valves to maintain venting on 15 and 16 March 2011.
- 374 The overall response strategy for Reactor Unit 3 can be summarised as:
- Cooling initially via RCIC.
 - Then HPCI cooling following failure of RCIC.
 - Then resort to cooling via alternative water injection into reactor via alternative means:
 - Depressurisation to permit alternative injection routes.
 - Via RCIC (attempted).
 - Fire system lines.
 - Switch to sea-water injection (presumably once fresh water supplies exhausted).
 - As for Reactor Units 1 and 2, considerable improvisation was required to re-establish control of key plant items and to obtain parameter information.
- 375 For Reactor Units 1, 2 and 3, the operators were able to benefit from modifications and procedures that had been undertaken for severe accidents that permitted use of the condensate make-up water systems and fire extinguishing systems to inject coolant into the RPV (see the Section [“Technology Used at the Fukushima-1 Site”](#)). All of the initial critical safety function strategies used appear to have been ones that were known and would have been included in EOPs and / or Severe Accident Management Guideline (SAMG) procedures. The operators appear to have attempted to invoke these strategies in a logical manner based on their understanding of the situation once information was available or plant conditions had been deduced. However considerable improvisation was required to operate plant and instrumentation, and provide water injection. The high degree of uncertainty on the plant state and lack of instrumentation would have been a major challenge, as were the physical conditions for undertaking local-to-plant actions.
- 376 Not all of the details of the attempted operator actions are known. It seems likely that additional actions were undertaken, including improvisations, particularly as cooling via the RCIC on Reactor Units 2 and 3 continued far longer than would otherwise seem possible.

Reactor Units 5 and 6

- 377 Reactor Units 5 and 6 were already shut down prior to the earthquake; the emergency diesel generators started on loss of AC power and RHR cooling continued to operate. When the tsunami struck the emergency diesel generators and RHR pumps failed on Reactor Unit 5, however one emergency diesel generator continued to operate on Reactor Unit 6. However RHR cooling was effectively lost due to the loss of the sea-water cooling (the ultimate heat sink). For both units the operators were faced with rising RPV pressures – this was more severe and rapid for Unit 5 due to the pressure leak testing at the time of the earthquake. At around 6am local time on the 12 March 2011 operators took actions to reduce the RPV pressure of Reactor Unit 5. On 13 March 2011 the

operators commenced water injection into both units using the condensate transfer pumps powered by the operating emergency diesel generator on Reactor Unit 6. Over the next few days the operators controlled reactor pressure and water level by opening an SRV and repeatedly filling the RPV with water from the condensate storage tank. On 19 March 2011 the operators restored RHR cooling by connecting temporary sea water to the RHR systems. Both reactor units achieved cold shutdown on 20 March 2011. The switch to external power supplies to Reactor Units 5 and 6 from reliance on the emergency diesel generators was achieved on 21 and 22 March 2011 respectively.

378 The overall response strategy for Reactor Units 5 and 6 can be summarised as:

- RPV pressure control.
- Water injection using water from condensate transfer pumps.
- Then switch RHR cooling once sea water pumps connected.

Spent Fuel Ponds

379 Following the earthquake and tsunami the spent fuel ponds and common pond effectively lost all active cooling. A similar situation faced the operators for each pond in that over a sufficient period of time the water would evaporate or boil, and ultimately leading to fuel uncover and potential release of fission products. Consequently there was a need to provide make-up water to the ponds to prevent this occurring. The greatest threat and urgency for response was for the spent fuel ponds for Reactor Units 1 to 4 due to the higher decay heat levels in these ponds. It is evident that there was considerable uncertainty over the conditions in the ponds for a considerable period (due to lack of parameter information) and hence the time available for action, and of the potential for other phenomena (e.g. zirconium fires, hydrogen generation and explosion). Access to the spent fuel ponds was also difficult due to the height above ground and the general damaged state of the buildings, particularly after the succession of explosions.

380 The conditions in the ponds degraded slowly, so no immediate response was required in the first few days following the tsunami. In response the operators attempted novel means of providing make-up water to the spent fuel ponds commencing with helicopter water drops on 17 March 2011 to Reactor Unit 3. These proved ineffective so the operators then switched to spraying Unit 3 pond using a ground-level water cannon. On 19 March 2011 cooling to Reactor Units 5 and 6 spent fuel pools was achieved once the temporary sea water pumps had been connected to the RHR systems - the RHR cooling was alternately switched from reactor cooling to spent fuel cooling. On 20 March 2011 water cannon spraying to Reactor Unit 4 spent fuel pool and sea-water injection to Reactor Unit 2 spent fuel pool commenced (method unknown). On 22 March 2011 Reactor Unit 4 spent fuel pond make-up was switched to using a concrete pumping truck. This method of providing make-up was then used on other ponds periodically over the next few days.

381 The overall response strategy for spent fuel pond cooling was essentially providing water make-up to the ponds. However this required considerable improvisation to devise effective means to achieve that given the state of plant damage and failed equipments. The overall response was:

- Water make-up via novel means (progressively more robust).
- Use of spent fuel cooling line for Reactor Unit 2 spent fuel pond.

- 382 It is worth noting that more urgent operator actions to provide make-up would have been required if the spent fuel ponds integrity had been breached and water lost by leakage. This would potentially have exacerbated the overall situation considerably.
- 383 The availability of mobile diesel generators and fire tenders within a relatively short time of the onset of the event allowed the operators to undertake many of the key improvisations to re-establish essential cooling for both the reactor units and spent fuel ponds at Fukushima-1, but not sufficient to allow a design accident basis. The OECC played an important role in supporting the operators in undertaking their response to the accident. This provided a relatively safe location that provided both a control and co-ordination centre to oversee the response; and a “safe haven” for plant operators where they could be briefed, prepared for on-site activities and rest during the protracted acute phase of the event. As noted by the IAEA mission it continues to play a key role in the longer term recovery and clean-up operations.

Fukushima-2 Operator Actions

- 384 The situation at the Fukushima-2 site was less severe than at the Fukushima-1 site, though it did come close to station blackout, and consequently the operators were able to follow emergency response plans more closely to control the four units. However there was still a need for notable improvisation in responding to the situation after the initial tsunami wave struck, followed by several additional waves. The tsunami caused flooding of the heat exchange building, sea-water pumps and electric power centres which caused loss of core cooling functions in three of the four units. The emergency diesel generators of Reactor Unit 1 were also flooded. The operators were able to bring Reactor Unit 3 to cold shutdown the day after the earthquake as this was the least affected unit. The operators were able to continue to provide water to the reactor cores with the RCIC and Make-up Water Condensate (MUWC) systems and to manually depressurise the reactors. Notable improvisations were the laying of more than 9km of temporary power cables in 16 hours and the use of mobile power trucks to restore electrical supplies to essential plant. This permitted RHR systems to be returned to service three days after the tsunami and the units were then successfully brought to cold shutdown by the operators within a day of restoring RHR cooling.
- 385 A summary of the operator actions is tabulated in [Annex K](#). Consideration of key human factors issues arising from the Fukushima events are given in the Section “[Human and Organisational Factors](#)”.

MAIN ASPECTS RELEVANT TO THE UK

Protection of UK Nuclear Installations from Natural Hazards

Overview

386 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

387 Within our SAPs, Ref. [5](#), there are very clear expectations laid out for the treatment of external hazards.

388 Within the Siting section of the SAPs it is stated that:

“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
<i>Natural and man-made external hazards should be considered if they have the potential to adversely affect the siting decision.</i>		

“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.”

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

Engineering Principles: External and Internal Hazards	Frequency of Exceedance	EHA.4
<i>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).</i>		

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

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 1×10^{-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
<p><i>A small change in DBA parameters should not lead to a disproportionate increase in radiological consequences.</i></p>		

- 390 In summary, the design basis for external hazards is based on events with annual probability of exceedance of 1×10^{-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.
- 391 Seismic and flood levels for UK nuclear licensed sites are summarised in [Annex G](#).

Seismic Hazards in the UK

- 392 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 known UK event in the historical and instrumental record 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.
- 393 The seismically active area closest to the UK that might 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 that produced by the smaller local earthquakes against which UK plant is shown to be robust.
- 394 The methodologies adopted for seismic hazard assessment for nuclear sites in the UK are probabilistic in nature. A broadly equivalent approach has been adopted in the United States, and is currently recommended in the IAEA guidelines. The typical values of peak ground acceleration at UK sites for a 1×10^{-4} pa probability exceedance range from 0.15g to 0.26g, considerably lower than those experienced at Fukushima.

- 395 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.
- 396 Although seismic events were not considered in the design basis of early nuclear plants in the UK, those designed after the early 1980s 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 (Ref. [5](#)). 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 PSR 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 these expectations of our SAPs.

Tsunami Hazards in the UK

- 397 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 a large-scale submarine landslide off Norway. Recently, public attention has been drawn to the disastrous flooding in areas bordering the Bristol Channel in January 1607, and there have been suggestions 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 directly generate tsunamis which will give rise to any noticeable effect.
- 398 A detailed study was undertaken in 2005 (Ref. [37](#)) 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 with local run-up effects potentially up to 4 meters. Typically, it is argued by Licensees that this increase is accommodated within the other contributors to sea level. These arguments are broadly accepted as being valid. However, there are inconsistencies in the detailed application of this method between Licensees.
- 399 In the intervening period since the production of these reports, there have been developments in the science of tsunami propagation and behaviour as well as research into historical events. It is considered that a review of new information be undertaken to confirm that the previous work undertaken remains valid.
- 400 Flood risks in the UK around nuclear licensed sites are discussed in [Annex F](#), and are considered within the safety cases for UK Nuclear Installations.

Event Combinations

- 401 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

- 402 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.
- 403 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.
- 404 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.

Generic Design Assessment

- 405 In Generic Design Assessment (GDA) we are currently assessing two new power station designs:
- The UK EPR™: PWR designed by EDF and AREVA.
 - The AP1000®: PWR designed by Westinghouse.
- 406 Information on the design of these reactors can be found on the website www.hse.gov.uk/newreactors/reactordesigns.htm.

The Advanced Gas-cooled Reactor Technology

- 407 Advanced Gas-cooled Reactor (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.
- 408 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.
- 409 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.

- 410 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.
- 411 Compared with light water reactors, 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)

- 412 Magnox reactors are the first generation of UK gas-cooled reactor. Only three, one 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 mainly natural uranium (although some fuel elements contain low enriched uranium) 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.
- 413 Oldbury and Wylfa have pre-stressed concrete pressure vessels but operate at a lower pressure and temperature than an AGR.
- 414 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 Technology

- 415 Nearly 60% 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™ and the AP1000® are evolutionary PWR designs which incorporate advanced features in various aspects of the technology as discussed in the following sub-sections.
- 416 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 4.4m, a thickness of 0.21m and an overall height of 13.6m.
- 417 The PWR fuel is cooled by water which also acts as the moderator. The reactor operates at a pressure of 155bar.
- 418 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™ 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® has two cooling loops each containing two reactor coolant pumps and a steam generator.
- 419 The fuel in a PWR is slightly enriched uranium dioxide which is contained within zirconium alloy cladding.

Reactivity Control

420 The three Fukushima-1 reactor units that were operating at power at the time of the Tohoku earthquake shut down 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 sub-sections discuss the reactivity control systems in the reactors in the UK.

Advanced Gas-cooled Reactors

421 Reactivity control in AGRs is achieved using the following systems:

- 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 an automatically initiated diverse shutdown system, in order to ensure shut down even if for any reason insufficient rods in the primary shutdown system insert into the core. At some stations the (fully) diverse system is based on rapid injection of nitrogen into the reactor core: nitrogen absorbs neutrons and hence stops the chain reaction. At other stations, the (partially) diverse system is based on an adaptation to the control rod system so that the rods are actively lowered into the core rather than falling under gravity and is then backed up by nitrogen injection manually initiated from the reactor control desk.
- A tertiary shutdown is provided to maintain the reactor in its shut down 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

422 Following a reactor, trip the nuclear reaction within a Magnox reactor would be shut down 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.

423 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 shut down of the reactor.

Sizewell B

424 Core reactivity control during normal operation and shut down 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.

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

- 426 If both systems fail the inherent characteristics of Sizewell B lead to an equilibrium situation in which core power matches heat removal. The operator can add boron using the chemical and volume control system.

Generic Design Assessment (UK EPR™ and AP1000®)

- 427 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

- 428 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-1 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 sub-sections discuss the post-trip cooling systems in the reactors in the UK.

Advanced Gas-cooled Reactors

- 429 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.
- 430 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.
- 431 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.
- 432 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 hours as discussed elsewhere in this report.

Magnox Reactors

- 433 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.

- 434 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.
- 435 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

- 436 Once the reactor is shut down decay heat removal can be provided by a number of systems as described below.
- 437 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.
- 438 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.
- 439 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®)

- 440 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.
- 441 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 of core make-up tanks, accumulators and gravity injection from the large in-containment water storage tank.

Containment

- 442 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

443 AGRs do not have a containment building around the pressure vessel. None of the design basis Loss of Coolant Accidents (LOCA) for AGRs 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. There are longer timescales available in the event of loss of post-trip cooling and the pressure vessel is a massive reinforced concrete structure. The AGRs 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

444 The generating 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. All of the first generation Magnox Reactors with steel pressure vessels are now permanently shutdown and depressurised.

Sizewell B

445 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™ and AP1000®)

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

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

Severe Accident Management

448 Once all the cooling capabilities were lost at Fukushima-1 Reactor Units 1 to 3, temperatures in the reactor cores increased rapidly and core degradation started. From the on-set 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 in an attempt to deal with 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.

449 All the reactors in the UK have in place arrangements to deal with situations of severe accident. These are set out below.

Advanced Gas-cooled Reactors

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

Magnox Reactors

451 The situation for the Magnox reactors is very similar to the AGRs, i.e. they have SAMGs.

452 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

453 Sizewell B has in place SAMGs (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. [38](#)):

- 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-loss of coolant accident (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™ and AP1000®)

- 454 Both reactor designs have engineered features to manage the severe accident scenario. The AP1000® design floods the outside of the RPV to retain the molten core inside the vessel. The UK EPR™ strategy is to cool any molten debris that escapes the vessel in a coolable concrete void (often called the core-catcher).
- 455 Both UK EPR™ and AP1000® have methods for reducing the risk of hydrogen explosions. The AP1000® relies on hydrogen igniters to burn the hydrogen before the atmosphere in the containment becomes explosive. The UK EPR™ relies on passive catalytic converters that remove any generated hydrogen from the atmosphere inside the containment.
- 456 Any future operators of either design will need to have in place adequate Severe Accident Management Guidelines (SAMG).

UK Reactor Site Spent Fuel Storage

- 457 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.
- 458 None of the operating UK reactors have identical fuel or spent fuel facilities to those at Fukushima. Unlike Sizewell B fuel, which is clad in a zirconium alloy, Magnox fuel assemblies are clad in a magnesium alloy whilst the AGR fuel is clad in stainless steel. Therefore, for the Magnox reactors and AGRs, 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.
- 459 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.
- 460 A summary of the spent fuel storage capabilities in the UK is provided below.

Advanced Gas-cooled Reactors

- 461 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 where 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

- 462 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.

- 463 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

- 464 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®)

- 465 UK EPR™ and AP1000® have similar strategies to those 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.

Relevant Aspects of UK Non-reactor Technology

Introduction

- 466 Because the accident at Fukushima involved nuclear reactors, it is more difficult to identify all of the relevant aspects on non-reactor nuclear technology used at nuclear installations in the UK. Nevertheless the following sections attempt to draw out those aspects for the UK nuclear installations, although it is recognised that the rigor of the response to the Interim Report recommendations and the application of the “Stress Tests”, which are being extended to non-nuclear power plant installations in the UK (see the Section “[Progress on European Council “Stress Tests”](#)”), may identify additional features.

Sellafield

- 467 The Sellafield site contains a large number of facilities, some associated with present day reprocessing of spent nuclear fuel, and others which contain legacy radioactive material inventory from reprocessing activities in the past.
- 468 The two main reprocessing facilities are the Magnox Reprocessing Plant and THORP which process Magnox and oxide fuel utilising solvent extraction processes.
- 469 Spent fuel is transported to the Sellafield site after a significant period of storage at the reactor sites to allow decay heat to reduce. The fuel is stored at Sellafield in cooled, water filled ponds

prior to processing and the loss of pond water / cooling is one of the accident scenarios covered by the current safety cases for the Sellafield fuel storage ponds.

- 470 The operations within the two main processing plants involve a number of mechanical and chemical processing stages. The hazards associated with the processing of the fuel material include radiological hydrogen generation, criticality and fire, and both plants have extensive protection systems and equipment to remove / mitigate the hazards, including the venting and ventilation of process vessels and cells.
- 471 The main products of the reprocessing plants are uranium and plutonium oxides. These products are stored in containers in purpose-built storage facilities. The plutonium oxide containers require some degree of cooling. In the more modern storage facilities, cooling is achieved by natural convective flow of air.
- 472 One of the major waste streams from the reprocessing plants is the highly radioactive, heat generating, fission product liquors which are transferred to water-cooled storage tanks for interim storage prior to vitrification (made into solid glass form) and long term storage in a natural convective air facility. The liquor storage tanks are fitted with a number of water cooling coils and jackets which, in an emergency, can utilise water supplied from a number of different water sources.
- 473 The other waste products from reprocessing processes are mainly exported to other treatment plants across the site. Much of the waste is cemented within storage drums and moved to a number of drum storage facilities. These drum storage facilities do not require any engineered cooling systems.
- 474 There are also a number of legacy facilities on the Sellafield site which carried out or supported reprocessing activities in the past. These legacy storage ponds and silos require a number of active and passive systems to control the risks / hazards from the radioactive material they contain, e.g. ventilation / inerting systems to prevent hydrogen accumulations and water cooling systems. The main focus on the Sellafield site is risk reduction by the removal of the materials from these legacy facilities to more robust modern facilities and the processing of the material into a safer, passive waste form. Many of these legacy facilities were designed and built in the 1950s and it is impossible to bring them up to modern standards.
- 475 Overall, the Sellafield site houses a large inventory of radioactive material across the site. Some of this material has heat-generating capability and some of the material is stored in a non-passive form in facilities which do not meet modern design requirements. However, the heat generating capability of the radioactive material on the site is lower than fuel in an operating nuclear power plant and thus accident scenarios generally develop over longer timescales than those modelled for nuclear power plants. Thus, the nature of the engineered safety and protection systems for the non-nuclear power plant facilities on the Sellafield site are significantly different to those for nuclear power plants. However, there are a number of key safety systems in various plants across the site, e.g. cooling, ventilation, inerting and containment systems and the availability and reliability of these systems under accident conditions forms the basis of the on-going Sellafield Limited review.

Commercial and Restoration Sites

- 476 Between them, the nuclear hazards related to the two regulatory programmes range from, at the higher end of the scale, those associated with the former operation and current decommissioning

of fast reactors at Dounreay, together with associated fast reactor fuel reprocessing and waste storage at the site, to recycling of bulk quantities of LLW-contaminated metal at the Studsvik Metal Recycling Facility site. Dounreay, Harwell, Winfrith, Springfields and URENCO are discussed below. Nuclear hazards at other commercial and restoration sites are minimal.

Dounreay

- 477 The former Dounreay Fast Reactor (14MWe) was designed to establish the feasibility of the fast breeder system and to provide information for the design of a full-scale power-producing fast reactor. Its fuel ponds have been emptied of fuel and are being decommissioned, and secondary systems have been removed. The primary liquid metal coolant is heavily contaminated with caesium-137 but is being progressively removed and destroyed using the purpose-built sodium destruction plant. About two-thirds of the approximately 50 tonnes of coolant have been destroyed to date. One driver fuel element and a large number of breeder elements remain in the core, which is subject to active inerting and hydrogen / fire detection systems. The former Prototype Fast Reactor (250MWe) was developed as the smallest reactor from which the information necessary for the design of commercial fast reactors could be obtained with confidence. It still stores some used fuel in the Irradiated Fuel Cave, which remains operational pending routing of the fuel to its final destination in due course as part of the decommissioning programme. Otherwise, the primary liquid metal coolant has been destroyed in a purpose built plant, and work to address removal of residual liquid metal continues. Secondary systems have been removed.
- 478 Elsewhere on the Dounreay site the Fuel Cycle Area (FCA), which used to reprocess fast reactor fuel, is now decommissioning. Active facilities include the original liquid effluent storage and treatment plant and the Dounreay Cementation Plant (DCP), a modern plant which stores solid Intermediate Level Waste (ILW). The liquid effluent storage and treatment plant, apart from storage and treatment of liquors, serves as the site control room and receives alarm and monitoring data from other plant on-site. There is currently an active batch programme for routing liquors from the plant to DCP for cementation, starting with raffinate from reprocessing of fuel from the Dounreay Materials Test Reactor. The FCA also houses nuclear material stores and former laboratories that are used for activities associated with waste and nuclear matter storage, and decommissioning. The Dounreay site also includes a below-ground silo formerly used to store solid ILW and a disused shaft formerly used to dispose of solid ILW. Both still contain the ILW under water shielding but are no longer in use. They are subject to active monitoring and are due to have their ILW removed and re-stored in due course. None of the material at Dounreay is such as to require cooling. Criticality controls and containment / shielding systems and other monitoring systems are as required by the safety cases for the various plants.

Harwell and Winfrith

- 479 The most significant nuclear hazards at Harwell and Winfrith are associated with care and maintenance of decommissioned de-fuelled reactors (Winfrith) and the storage and handling of ILW and nuclear matter (Harwell). None of this activity requires active cooling. Containment / shielding systems and other monitoring systems are as required by the safety cases for the various plants.

Springfields and URENCO UK

- 480 The main nuclear hazards in fuel manufacture at Springfields and UUK relate to criticality safety, with the dominant hazard being the chemo-toxicity associated with the manufacture and processing of uranium hexafluoride.

Atomic Weapons Establishment, Aldermaston and Burghfield

- 481 AWE is managed for the MoD through a contractor-operated arrangement. Both sites and facilities remain in Government ownership, but their management, day-to-day operations and maintenance is contracted to a private company. Nuclear site licences were granted to AWE plc as operator of the sites.
- 482 AWE manufactures and maintains the warheads for the UK's Trident submarine-launched nuclear deterrent.
- 483 Trident is an inter-continental ballistic nuclear missile weapons system, carried by Royal Navy Vanguard Class submarines. The role of AWE is to manufacture and sustain the warheads for the Trident system, ensuring optimum safety and performance, but also to maintain a capability to produce a successor system should the Government require one in the future.
- 484 The work at AWE covers the entire life cycle of nuclear warheads: From initial concept, assessment and design, through to component manufacture and assembly, in-service support and, finally, decommissioning and disposal.

Nuclear Fuel Production Plant and Neptune Reactor, Derby, Derbyshire

- 485 RRMPOLE operates two nuclear licensed sites in support of the MoD Naval Nuclear Propulsion Programme. RRMPOLE operates the Neptune zero-power test reactor used in the research and design of naval reactor fuels, and manufactures the nuclear fuel that powers the Royal Navy's submarines.

Devonshire Dock Complex, Barrow-in-Furness, Cumbria

- 486 The Devonshire Dock Complex is a shipbuilding facility operated by BAESM as the site licence company. The complex includes the Devonshire Dock Hall, a large indoor facility that was used to construct the Vanguard Class submarines and where currently the Astute Class submarines are being constructed. Within the complex, a ship lift facility is utilised to lower vessels into the water without reliance on tidal conditions. As well as construction, the commissioning and testing of submarines take place within the facility. New fuel for the reactor is stored on-site before it is loaded into the reactor pressure vessel prior to testing.

Devonport Royal Dockyard, Plymouth

- 487 The Devonport site consists of two parts, the Naval Base and Devonport Royal Dockyard. The MoD manages the Naval Base, which is under the control of the Naval Base Commander and is currently the base port for a number of Trafalgar Class hunter-killer submarines. Devonport Royal Dockyard is that part of the overall Devonport site owned and operated by the Marine and Technology Division of Babcock International, which includes the site licence company DRDL, which operates the nuclear-related facilities. DRDL is contracted by MoD to refit and maintain the Royal Navy's

nuclear powered submarines. A number of redundant submarines are stored afloat at Devonport awaiting development of a new facility to remove the spent fuel from some of them.

Rosyth Royal Dockyard

488 Rosyth Royal Dockyard was used to support the refitting and maintenance of nuclear powered submarines until such work was transferred to Devonport. The nuclear licensed site is a relatively small part of the overall dockyard and most of the nuclear-related facilities have now been decommissioned and the hazard removed. Relatively small quantities of radioactive wastes are currently stored on the site and disposal routes for these are currently being explored.

HUMAN AND ORGANISATIONAL FACTORS

Human Factors

Severe Accident Management Strategy in the UK

- 489 As noted previously, in the UK, post-fault operator actions on power reactors are usually 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 generally 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.
- 490 Typically, during the transition between Symptom Based Emergency Response Guidelines (SBERG) 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 usually becomes one of action implementation. This may need to be reviewed in the light of the experience at Fukushima-1.
- 491 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 as, typically, emergency exercises focus on design basis events (although they are extended to test off-site response to release scenarios). However, there have been instances where exercise scenarios have extended into severe accident territory; facilitating training in the application of SAGs. Again, this may need to be reviewed.
- 492 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.** However, the industry has undertaken a range of assessment relating to severe accident situations, including their treatment in periodic safety reviews, qualitative reviews of SAG usability, and the piloting of Level 2 PSA for example. In recent years ONR has actively encouraged the industry to pursue these activities in order to enhance their knowledge on, and understanding of, the potential severe accident sequences, in particular for the gas cooled reactors, and the Industry’s ability to cope with, and manage potential severe accidents.

Implications for UK Power Reactor Facilities, Including New Nuclear Build

- 493 As with our Interim Report, the focus of the human factors implications, lessons to be learnt and recommendations relates to severe accident management in general, rather than the response to the specific hazard affecting the Fukushima-1 reactor units.

** 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.

494 The following paragraphs principally refer to nuclear power reactors. This does not imply that severe accidents are not of concern for other types of nuclear installations: all licensees need to address the potential for severe accidents at their installations, and their ability to manage the various potential accident sequences.

Availability of Personnel for Severe Accident Management

495 This was a key issue and directly relevant to UK severe accident management.

496 Generally, UK safety cases make assumptions about the availability of personnel in defined off-site locations, within a specific timescale.

497 We have undertaken some preliminary work relating to the likelihood of external hazards simultaneously affecting a nuclear licensed site and the off-site technical support centre, and our initial conclusions are that coincident damage to both the nuclear facility and to the off-site centre from significant external hazards cannot be dismissed. We therefore expect this to be examined in more detail by the industry.

498 We note the availability of a seismically robust building for the operation of the emergency response centre in Japan, and that the building provided the only safe place in the vicinity of the plant to house a large number of people (over 200) engaged in the recovery operations. The robustness and capacity of off-site buildings that may act as technical support centres or emergency response centres is important.

499 Minimum manning levels for licensed sites are not prescribed in the UK either for routine operations or fault and emergency conditions / events. Site emergency plans define on-site roles and will typically have an on-call rota for a limited number of off-site staff to be available in an event (usually within an hour). At Fukushima 400 people were available for the recovery, which was insufficient for the recovery of six units. The availability of personnel and adequacy of manpower for multi-unit emergencies that may extend for weeks / months will be an important element of severe accident management strategies. Manpower requirements to provide emergency supplies and equipment, and to support the event control effort in hostile environments, are also important.

500 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 the 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 training and procedural support.

501 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). The availability and number of on-site personnel could be affected by external hazards.

502 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 commend the operators and wider emergency support teams at Fukushima, however we consider a greater understanding of the

^{§§} In December 1984 a gas leak from a small pesticide plant devastated the city of Bhopal, killing over 2500 people and injuring more than 200,000. The immediate cause of the discharge was an influx of water into a methyl isocyanate storage tank.

literature in this area would be useful to inform UK safety cases. We are aware of the literature highlighting the effects of physiological changes under threat conditions leading to a reduction in cognitive functions such as working memory, and this knowledge may be valuable for future developments in severe accident training and procedural support. Additionally the literature on acute and chronic stress at the individual and team level support for (prolonged) severe accidents can provide useful information. The influence of national cultures on behavioural response (individual and team) is also relevant

Technical / Procedural Support - Severe Accident Management Guidelines

- 503 The Interim Report recommended a review and potential extension of severe accident contingency measures. Important features of this review will include critical safety functions prioritisation, and whether and how the SAMG support any dynamic re-prioritisation of goals, criteria and objectives based on emerging plant predictions and prognoses, and whether any customisation of SAGs is required to account for station differences and their risks to external hazards. We also acknowledge that this may result in a requirement for research to improve understanding of AGR and PWR accident phenomenology.
- 504 Furthermore, it is clear from the Fukushima event that the accident was significantly outside of what is covered by the SAMGs, and that the guidance was not adequate to cope with multiple plant failures. For example, it is known that the Fukushima procedures did not anticipate the full impact of the tsunami, and only specified the operation of stopping circulating water pumps used for cooling condensers as measures against undertow.
- 505 In addition, SAMGs usually assume the availability of instrumentation, lighting and power, and do not generally consider the potential state of the plant and locality that may affect the potential for and reliability of manual actions; this will require consideration and revision as SAMGs develop and move forward in the UK.
- 506 The value and importance of modern standard Level 2 PSA to the development of severe accident management strategies and SAMGs should not be underestimated.

Operator Training and Severe Accident Rehearsal

- 507 There do not appear to be any implications that a lack of operator training contributed to or exacerbated events at Fukushima. However, there are implications and lessons cited relating to the overall functioning of the emergency organisation. For example, it is recognised that it took time to establish communication between the plant and the emergency response centre, and to build a collaborative structure with the emergency services and armed forces. It is noted that adequate training and rehearsal of the complete emergency organisation may have prevented such problems, together with more robust communication facilities.
- 508 In the UK, it is typical to rehearse the operation of the emergency organisation, including external agencies and services. However, it is not typical to exercise severe, long timescale, multiple hazard events affecting multiple units, involving large numbers of people.
- 509 We recognise the limitation of current reactor simulator models to support the formal training of severe accident management. However, we consider that the industry should extend and augment the current training provision at the operator and organisational level.

- 510 Training of external, technical non licensee staff that could be made available to support the event mitigation and recovery effort in large-scale severe accidents is important. We recognise the general shortage of nuclear skills in the UK, and commend the efforts being made by a number of organisations to address this. We particularly consider the National Skills Academy's Nuclear Passport Scheme as a credible mechanism for the basic training of a large number of personnel that could be utilised in an event of the scale of Fukushima.
- 511 The clean-up and recovery activities are continuing at Fukushima, some months after the acute phase of the accident. IAEA have noted good practices relating to the Fukushima clean-up and recognise that there are lessons to be learnt in this area. Generally, in the UK, there is no detailed consideration given to the resources and facilities required, and co-ordination and control of such activities. This is of particular importance in terms of the arrangements for radiological monitoring and protection of workers, and the need to train many contract workers who may have little or no familiarity with the hazards on a nuclear site.

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

- 512 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 and temporary) engineered measures that can be employed in a severe accident.
- 513 Current UK safety cases do not generally consider the near-total loss of 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, data availability (and the scope of equipment qualification) in a severe accident situation is vital.
- 514 Control room habitability should be maintained in severe accidents. It is clear from Fukushima that the poor habitability of the control room led to delays in operational decision-making. When the accident occurred, the radiation dose increased in the control room and operators evacuated temporarily. The availability of, and protocols for, communication facilities in a severe accident situation are also important.
- 515 We note and support the IAEA findings relating to the availability of equipment and communication; in particular the importance of having a clear understanding of the hazard and risk potential, to ensure that (pre-staged, portable) equipment is available to carry out essential safety functions in a location that limits the probability of damage by the external event. Pre-staging of remote-controlled equipment in light of potential radiation levels could be of value.

Organisational Factors

- 516 The reports published to date on the lessons from Fukushima do not consider in any depth the underlying leadership and cultural factors. In addition, there is very little factual information relating to the decision-making process or the command and control philosophy and its effect on behavioural response. There are indicators of leadership and safety culture issues evident in the various reports and public domain material, and we recognise the significant cultural differences

between the UK and Japan; but in the absence of any organisational analysis it is difficult to draw evidence-based conclusions. We will, of course, consider any emerging evidence and organisational analysis of the Fukushima accident for further lessons to be learnt relating to leadership and cultural factors for the UK.

- 517 In line with international good practice following major events, an independent investigation into contributing organisational and cultural factors should be undertaken. IAEA could play an important role in this investigation.
- 518 We note that the report from the government of Japan to the IAEA Ministerial Conference on nuclear safety in June 2011 (Ref. [2](#)) includes a lesson (Chapter XII, Lesson 28), on the need to thoroughly instil a safety culture. It emphasises that, without a safety culture, there will be no continual improvement of nuclear safety, and commits to maintain an attitude of trying to identify weaknesses. This is akin to an attribute often associated with High Reliability Organisations (HRO); namely a preoccupation with avoiding failure and looking for early warning signs.
- 519 These points from Fukushima resonate with the lessons from major events in a range of sectors (e.g. loss of the space shuttle Columbia, explosion at the Texas City oil refinery, loss of the Nimrod aircraft over Afghanistan). The persistent nature of such lessons across a wide range of sectors and countries highlights to all those with responsibilities for safety, and its regulation, the importance of understanding and continually applying the learning. Knowing the lessons is not sufficient; appropriate action needs to be taken and improvements sustained. This is part of a continuous improvement culture.
- 520 ONR has recognised the importance of culture and appropriate leadership for nuclear safety along with the need for learning organisations. A key aspect of ONR's published plan is that the UK nuclear industry has a culture of continuous improvement and sustained excellence in operations. A key role for ONR is to influence change to create an excellent health, safety and security culture amongst operators, and to promote sustained excellence in nuclear operations.
- 521 In 2006 SAPs (Ref. [5](#)) were published on leadership and management for safety. These provide a foundation for nuclear safety including instilling a positive safety culture. The principles encompass leadership, organisational capability, decision-making and learning. They were informed by lessons from world-wide major events and by the attributes of HROs.
- 522 ONR developed a strategy to apply these principles on leadership and management for safety. The goal of the strategy is to influence and encourage licensees to achieve and maintain high standards of leadership and management for safety, and a strong safety culture, through co-ordinated and sustained regulatory activities. Specific objectives of the strategy include: improving awareness within ONR and licensees of leadership and cultural factors; embedding attention to leadership and safety culture into ONR's regulatory activities; and putting more ONR focus on interactions at board, director and senior management levels in licensees.
- 523 ONR is part way through the process of implementing this strategy. It will require further work and sustained focus to ensure the objectives of the leadership and management for safety strategy are achieved and the changes are embedded successfully into ONR's way of working.

Doses to Intervention Personnel

- 524 With regard to the Japanese response to the nuclear emergency at the Fukushima-1 site, it has been necessary for some of 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, whole body doses up to 250mSv have been authorised, and 30 people closely involved with the emergency have received whole body doses between 100–250mSv.

- 525 Radiation exposure management for staff involved in remedial actions was hampered by the damage that had been caused by the tsunami to electronic personal dosimeters and readers, air contamination monitors, and other equipment. Whilst the Fukushima experience highlighted these particular items, they are part of a larger picture of intervention resources, and in different circumstances the emphasis might fall on other aspects. It is therefore important to apply the learning by reviewing the vulnerability of accident response equipment and resources to those accidents for which they would be needed, and ensuring that arrangements are robust.
- 526 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 (REPPPIR) disapply the normal dose limit for the purposes of intervention. REPPPIR requires operators to notify HSE in advance of the dose levels they have determined to be appropriate for intervention workers in the event of a radiation emergency. The UK and REPPPIR framework applied to the determination of dose levels for intervention personnel is consistent with that declared by IAEA and ICRP.

Public Protection Countermeasure Zone

- 527 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. The information provided since the Interim Report continues to give assurance that the arrangements are generally effective in protecting the public.

Distribution of Potassium Iodate Tablets

- 528 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 for distribution to UK nationals to take if they were likely to be exposed to a significant cloud of radioactive iodine.
- 529 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, Casualties and Intervention Personnel

- 530 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. Radiation doses to the limbs are less damaging than radiation doses to soft tissues and organs.
- 531 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

- 532 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. Furthermore, reliable monitoring results are likely to inform decisions on changes to countermeasure advice. 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 Centre for Radiation, Chemical and Environmental Hazards (CRCE) 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

- 533 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 permitted level of iodine-131 in fishery products.
- 534 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 EU. These are based on the aversion of a dose of 1mSv, assuming contaminated food is being consumed at the indicated level of contamination for a whole year.
- 535 If it is assessed that levels of radioactivity in any potential food products may exceed the CFILs as a result of an accident, the FSA will describe the area in which the relevant CFILs might be exceeded, name the food products affected and advise on the actions to be avoided (e.g. eating, collecting, harvesting or transporting).
- 536 FSA is 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.

- 537 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.
- 538 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.
- 539 Significant quantities of contaminated water were discharged to sea, and continue to be held on-site. This is relevant to light water reactor cooling requirements in severe accidents, and may also be relevant for some waste / spent fuel stores at other sites. This is an area for consideration under the Interim Report recommendations.

Robustness of the UK Grid

- 540 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 NPP 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.
- 541 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.
- 542 Although the grid provides a reliable source of power in normal conditions, operators of nuclear plants are required to provide on-site sources of standby generation 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 earthquake or severe weather, the grid system could be subject to disruption by the same events as the nuclear power plant. Thus, it is 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 plants are required 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. Indeed all UK licensees need to ensure that the capabilities of their electrical supplies, including any required back-up supplies, are sufficient to ensure that they can sustain safe operation in case of loss of grid.

Emergency Arrangements

- 543 There has been considerable activity regarding co-ordination of UK emergency arrangements for nuclear installations. The Nuclear Emergency Planning Liaison Group (NEPLG) has conducted an initial review of emergency arrangements with particular regard to dealing with a prolonged event similar to the devastating one at Fukushima. This is in direct response to Recommendation IR-3 of the Interim Report.
- 544 DECC has the lead department role in bringing together organisations involved in off-site nuclear emergency preparedness and response through the NEPLG. The initial review was held on 26, 27 and 28 July 2011, when attendance was made by the multi-agencies that contribute to nuclear emergency planning within the UK. Furthermore, two more review sessions are planned to be held during September and November 2011.
- 545 It should be noted that the IAEA Integrated Regulatory Review Service mission to the UK in October 2009 considered the creation of the NEPLG to be a *Good Practice* in supporting the multi-agency response in the UK. NEPLG therefore believes it is well placed to conduct this review on behalf of HM Chief Inspector of Nuclear Installations.
- 546 The initial review conducted by NEPLG focused in particular on four key areas:
- Radiation monitoring capacity and capability and co-ordination including radiation monitoring units co-ordination, food and the environment.
 - Central government response.
 - Extendibility.
 - Capacity and capability of emergency services including emergency exposures.
- 547 NEPLG found current arrangements to be fit for purpose. In light of the events in Japan, however, a number of opportunities for strengthening arrangements have been identified. A programme of work has been instigated to address the issues found to require strengthening.
- 548 Further detail with regard to the programme of work can be found within the response to Recommendation IR-3 described in the Section "[Recommendations Relevant to NEPLG – Recommendation IR-3](#)" and information will be published on the DECC website as the work progresses.

RESPONSES TO INTERIM REPORT RECOMMENDATIONS

549 HM Chief Inspector of Nuclear Installations' Interim Report raised 25 recommendations focused on determining whether any reasonably practicable improvements to the safety of the UK nuclear industry can be made. The Interim Report recommendations are reproduced below:

General	
International Arrangements for Response	Recommendation IR-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	<p>Recommendation IR-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.</p> <p>Recommendation IR-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.</p>
Openness and Transparency	Recommendation IR-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 IR-5: Once further detailed information is available and studies are completed, ONR should undertake a formal review of the Safety Assessment Principles to determine whether any additional guidance is necessary in the light of the Fukushima accident, particularly for "cliff-edge" effects.
Emergency Response Arrangements and Exercises	<p>Recommendation IR-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.</p> <p>Recommendation IR-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.</p>

Relevant to the Nuclear Industry	
Off-site Infrastructure Resilience	<p>Recommendation IR-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.</p> <p>Recommendation IR-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.</p>
Impact of Natural Hazards	<p>Recommendation IR-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.</p>
Multi-reactor Sites	<p>Recommendation IR-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.</p>
Spent Fuel Strategies	<p>Recommendation IR-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.</p>
Site and Plant Layout	<p>Recommendation IR-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.</p>
Fuel Pond Design	<p>Recommendation IR-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.</p>
Seismic Resilience	<p>Recommendation IR-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.</p>
Extreme External Events	<p>Recommendation IR-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.</p>
Off-site Electricity Supplies	<p>Recommendation IR-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.</p>
On-site Electricity Supplies	<p>Recommendation IR-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.</p>

Relevant to the Nuclear Industry	
Cooling Supplies	<p>Recommendation IR-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.</p> <p>Recommendation IR-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.</p>
Combustible Gases	<p>Recommendation IR-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.</p>
Emergency Control Centres, Instrumentation and Communications	<p>Recommendation IR-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.</p> <p>Recommendation IR-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.</p>
Human Capabilities and Capacities	<p>Recommendation IR-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.</p>
Safety Case	<p>Recommendation IR-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.</p>

Way Forward	
Way forward	<p>Recommendation IR-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.</p>

- 550 The recommendations are aimed at a number of organisations including the Government, the Nuclear Emergency Planning Liaison Group (NEPLG), ONR and the wider nuclear industry. The 26th recommendation within the report stated that a response to the recommendations should be provided by relevant organisations within one month of the Interim Report being issued (i.e. by 17 June 2011) and that these responses should include appropriate plans for addressing the recommendations.
- 551 This section of the report discusses the responses that have been received in the context of whether they provide an appropriate commitment to fully address the scope of the recommendations, and whether the plans that have been provided are sufficient at this stage.
- 552 Given the nature of the recommendations and the relatively short timescale since they were made, at this stage ONR expects the industry to be developing plans and projects to address the recommendations and has met the licensees to confirm this. None of the recommendations have yet been completed; however, an appropriate degree of progress is evident. As the reviews requested by the recommendations are completed, it is intended that the outcomes (e.g. plant modifications, provision of additional off-site emergency equipment, modifications to procedures etc.) will transition into normal business processes for delivery.
- 553 ONR notes that many of the responses from the nuclear industry have used a standard pro forma in responding to each recommendation. This pro forma asks a series of questions and was developed and agreed by the nuclear industry's Safety Directors' Forum (SDF). ONR welcomes this initiative which has helped to provide a consistent and appropriate response from the nuclear industry.
- 554 It should also be noted that whilst initial responses were received within one month of the HM Chief Inspector of Nuclear Installations' Interim Report being issued, as requested. In many cases these responses have been updated to include an additional section on progress and to take into account comments provided by ONR. These updates were received by ONR by the end of July 2011 and have been taken into account in this report

Recommendations Relevant to the Government – Recommendation IR-1

- 555 The Government's response was as follows:
- 556 The Government will continue to work with its partners in the G8, G20 and other international organisations to ensure better compliance with international conventions and push forward work on enhancing nuclear safety standards established under the auspices of IAEA.
- 557 In conjunction with our partners, we have called upon IAEA to consider the relevant standards to identify issues that may warrant examination and revision in the light of the Fukushima accident.
- 558 We are also committed to working with our international partners to consider how dissemination of information under the Convention on Early Notification of a Nuclear Accident can be further improved in terms of both efficiency and substance.
- 559 Domestically, the Government has formed a technical co-ordination group to consider how the results of national radiation monitoring are collated across the relevant departments and agencies and communicated to the public - with the aim of making this as clear and informative as possible. It is also noted that IAEA are producing an action plan that is anticipated to respond to the Government's prompting in this area.

Recommendations Relevant to the Government – Recommendation IR-2

- 560 The Government's response was as follows:
- 561 The Government will carry out a review of the Japanese response to the Fukushima emergency. The review will build on the UK's existing robust and well-exercised plans for civil contingencies (including nuclear emergencies), and will be strongly informed by relevant findings presented by HM Chief Inspector of Nuclear Installations to IAEA following the recent international fact-finding mission to Japan.
- 562 The UK's planning for civil contingencies already takes into consideration key groups of people (e.g. vulnerable people, victims and responder personnel) and, in the case of civil nuclear emergency planning, includes regular exercises involving the site operator, local authority, central government and others. Building on these existing arrangements, and in line with the Interim Report, the review will also take into account social, cultural and organisational factors. In doing this we will take the opportunity to consult with our embassies worldwide, to take into consideration broad-ranging cultural aspects of people's behaviour during emergencies.
- 563 Also in line with the Interim Report the review will include a strong focus on ensuring that the UK's evacuation plans for a wide range of civil contingencies, including nuclear emergencies, are robust, practical and appropriate to the UK context. We will complete the review before the end of the year.

Recommendations Relevant to NEPLG – Recommendation IR-3

- 564 NEPLG responded as follows:
- 565 In response to Recommendation IR-3 of the Interim Report, NEPLG has conducted an initial review of emergency arrangements for dealing with a prolonged event at a nuclear site, similar in scale to that at Fukushima.
- 566 NEPLG currently has published "*Consolidated Guidance*" (Ref. [39](#)) that sets out the response to emergencies at nuclear sites in the UK and overseas. NEPLG however did identify a number of opportunities to strengthen these arrangements, including:
- radiation monitoring;
 - central government response;
 - emergency services' capacity and capabilities; and
 - extendibility.
- 567 The opportunities identified by NEPLG will form part of a wider programme of work being taken forward by DECC. The timelines for this programme (and any work NEPLG does) will be finalised in October, and will be taken forward by the department as a priority. This will include updating DECC's published guidance on the UK's response to an overseas nuclear incident by December 2011.

Radiation Monitoring

- 568 NEPLG considered the adequacy of current radiation monitoring capabilities in the UK and, whilst the strengths of the existing arrangements were acknowledged, a number of areas of improvement were identified. In particular, whilst *Radiation Monitoring Co-ordination* (Chapter 15) provided

general information on the UK's radiation monitoring capabilities, *Consolidated Guidance* lacked detailed information about the UK's radiation monitoring capacity. NEPLG will improve this by addressing the need for a description of the UK's capability for hazard assessment and consider the UK's radiation monitoring arrangements more fully in guidance.

Central Government Emergency Response Arrangements

569 *Consolidated Guidance* sets out the central government response to an emergency at a nuclear site based on the reference accident. However, NEPLG recognised a number of opportunities for strengthening these arrangements, listed below.

570 NEPLG considered central government response arrangements for a nuclear emergency in the UK based on current planning assumptions. It believes the current arrangements are fit for purpose, and also identified a number of opportunities for strengthening arrangements, including:

- producing a common response framework for all types of event at nuclear sites;
- ensuring that the provision of science / technical advice for any event at a nuclear site is timely and lines up with best practice; and
- further opportunities for working with local and national agencies to optimise the response to an event:
 - reviewing the interfaces and roles of groups such as Scientific and Technical Advice Cell (STAC), Nuclear Emergency Briefing Room (NEBR), Scottish Government Resilience Room, SAGE; and
 - reconciling key scientific roles which include Government Chief Scientific Adviser, Government Technical Adviser, Director of Public Health and HM Chief Inspector of Nuclear Installations.

571 Regarding the central government response to an overseas accident, the NEPLG will carry out a detailed review of the *Overseas Nuclear Accident Plan* and the future testing of these plans.

Emergency Services' Capacity and Capabilities

572 Preparedness and response for the emergency services and how they work together, in any kind of emergency, have improved in recent years. However, notwithstanding this fact, there are lessons to be learnt from Fukushima and these will be taken forward in part through the Government's response to Recommendation IR-2.

573 NEPLG believes that within the UK there has been limited opportunity to test emergency service capacity and capability in the event of a prolonged radiation emergency at a nuclear site. Given the potential demand on current specialist responders, NEPLG has identified the need for a consistent radiation protection and intervention framework for all emergency services throughout the UK, and is currently developing a *Working Together Agreement* or *Memorandum of Understanding* between nuclear site operators and emergency services responders.

Extendibility

- 574 Extendibility concerns circumstances where it is necessary to expand countermeasures beyond the DEPZ.*** NEPLG concluded that the concept of extendibility is right, however it has concluded that further work on the stress testing of these extendibility concepts will need to take place to ensure that the planning is appropriate for the full range of emergencies at nuclear sites. NEPLG also identified a need for consistent guidance on planning for the DEPZ (the DEPZ for nuclear sites is typically between 1–3km around a site) and the importance of ensuring effective and more regular testing of extendibility arrangements. It is important to continue to determine emergency planning zones on a site-by-site basis.
- 575 DECC are currently taking forward detailed work (separate from but complementary to the Government's response to the Interim Report review) on the risk assessment, planning and response to potential emergencies of any scale at nuclear sites within the UK (or abroad).
- 576 The DECC website provides a detailed record of the work of NEPLG and its sub-groups as this continues to evolve.

Recommendations Relevant to the Regulator (ONR) – Recommendation IR-4

- 577 Since ONR was established, on 1 April 2011, it has reinforced its commitment to become a more open and transparent regulator. At the ONR Board's first meeting, in June 2011, the interim ONR Chair, Mr N Baldwin, also gave a personal commitment to ensuring that ONR is an open and transparent organisation and an effective and efficient regulator. He has met a wide range of stakeholders, including the industry and Government departments, to understand their views of ONR.
- 578 The ONR Board has also committed to follow Government policy on openness and to publishing all papers on the ONR website (including partial closures with redactions) unless closed under the Freedom of Information Act 2000 or the Environmental Information Regulations 2004.
- 579 As part of a wider change programme ONR has a programme of work in place, which is working towards making the most of its regulatory decision-making documents publicly available on its website.
- 580 Following publication of the Interim Report, ONR has started a series of meeting with non-governmental organisations, with minutes available on the website. Meetings with all stakeholders, including industry, are intended to promote an open exchange of views and feedback on nuclear regulation. The on-going engagement provides ONR with an opportunity to explain how ONR works, understand respective positions, and to exchange views.
- 581 ONR has also started to engage with licensees to share and generate ideas for improving openness and transparency across the industry. A survey which includes questions about ONR's openness and transparency in decision-making will be used as a benchmark to measure the organisation's progress. These results will be published once available. ONR is working with EDF Energy in identifying real measures for both organisations to actively improve openness and transparency. Over the coming months, ONR plans to widen this work to include other operators.
- 582 ONR is also publishing a corporate quarterly report, which will inform the public and stakeholders about key regulatory issues and priorities; plans for improving nuclear safety; work towards

*** The DEPZ for nuclear sites is typically between 1–3km around the site.

becoming an independent statutory body; and measures that ONR is pursuing to improve regulatory effectiveness.

- 583 ONR will continue to develop openness and transparency in its work, and will encourage the industry to follow suit. This will be reported in its monthly stakeholder eBulletin and quarterly report.

Recommendations Relevant to the Regulator (ONR) – Recommendation IR-5

- 584 In the Interim Report we noted, in Conclusion 4, that the circumstances of the Fukushima accident had not revealed any gaps in our SAPs (Ref. 5) at that time. Nevertheless, we recognised that further information and analysis would become available and Recommendation IR-5 is for ONR to undertake a review of our own SAPs and guidance to determine whether additional guidance is necessary in the light of the Fukushima accident. During the time since publication of the Interim Report we have reviewed further information that has become available to us and have identified a number of areas where we consider further guidance may be helpful (see the “[Discussion](#)” section of this report) in our SAPs or TAGs.
- 585 However, we consider that Recommendation IR-5 is best addressed taking account of other recommendations that we have placed on the UK nuclear industry and others, together with the outcomes from the European Council “Stress Tests”. In particular, the conclusions from the peer review process of the “Stress Test” results could realistically lead to new insights (or an international consensus) that will need to be taken into account in ONR guidance.
- 586 Although it is only six years since the last major update of the SAPs, there are a number of areas where our guidance might reasonably be improved, e.g. in light of our experience working to them to provide further clarification and guidance. The work for Recommendation IR-5 will seek to deliver these improvements alongside changes deriving from the Fukushima accident.
- 587 We will address Recommendation IR-5 in an effective manner by integrating this work within our normal work programme using our existing Nuclear Topic Group system to deliver the review. We envisage a staged approach:
- Stage A: Initial Nuclear Topic Group review and output from this report.
 - Stage B: Augment Stage A with findings from “Stress Tests” and response to recommendations.
 - Stage C: Augment Stage B with findings from “Stress Test” peer reviews.
 - Stage D: Update SAPs and TAGs - from May 2012 onwards.
- 588 IAEA has begun a similar process to update its own Safety Standards as a result of the Fukushima accident. Their process will however be running to a somewhat slower timetable than ours, reflecting the logistical difficulties in consulting worldwide on these documents. IAEA expects to start taking active account of the accident in its published guidance over the next few years. There will, therefore, not be any direct interface between our project and IAEA’s; instead we will need to be alert to changes coming from IAEA and then update our guidance as necessary on a case-by-case basis.

Recommendations Relevant to the Regulator (ONR) – Recommendation IR-6

- 589 Recommendation IR-6 was that ONR considers to what extent long-term severe accidents can and should be covered by the programme of emergency exercises overseen by the Regulator.
- 590 The Interim Report indicates that there is a need to consider extending some emergency exercises in the UK to include severe accident scenarios. The extensive and extended nature of the Fukushima accident high-lighted areas where improvements may be made through exercising in real time such matters as handover arrangements, sustainability of resourcing, the provision of technical advice in short timescales (tailored to the needs of the different recipients) and the vital role of communications and the acquisition of reliable data.
- 591 As a result we have initiated a review of the existing programme of exercises to evaluate how changes to exercise scenarios supported by longer exercise duration will permit exercising in real time such matters as hand-over arrangements etc. It will also look closely at how automatic decisions taken to protect the public can be confirmed and supported by plant damage control data. It will then make recommendations on what should be included in an appropriate UK exercise programme for testing nuclear emergency plans. Relevant guidance will be provided to REPIIR duty holders.
- 592 ONR aims to produce a report on this review by the end of the year.

Recommendations Relevant to the Regulator (ONR) – Recommendation IR-7

- 593 ONR's response to the Fukushima accident is well reported within our Interim Report published in May 2011. Although stakeholders have fed-back positively regarding our response, such as our provision of authoritative advice to Government, we are not complacent and are always striving to continuously improve. [Figure 10](#) illustrates the current improvement workstreams relevant to ONR's emergency arrangements function.

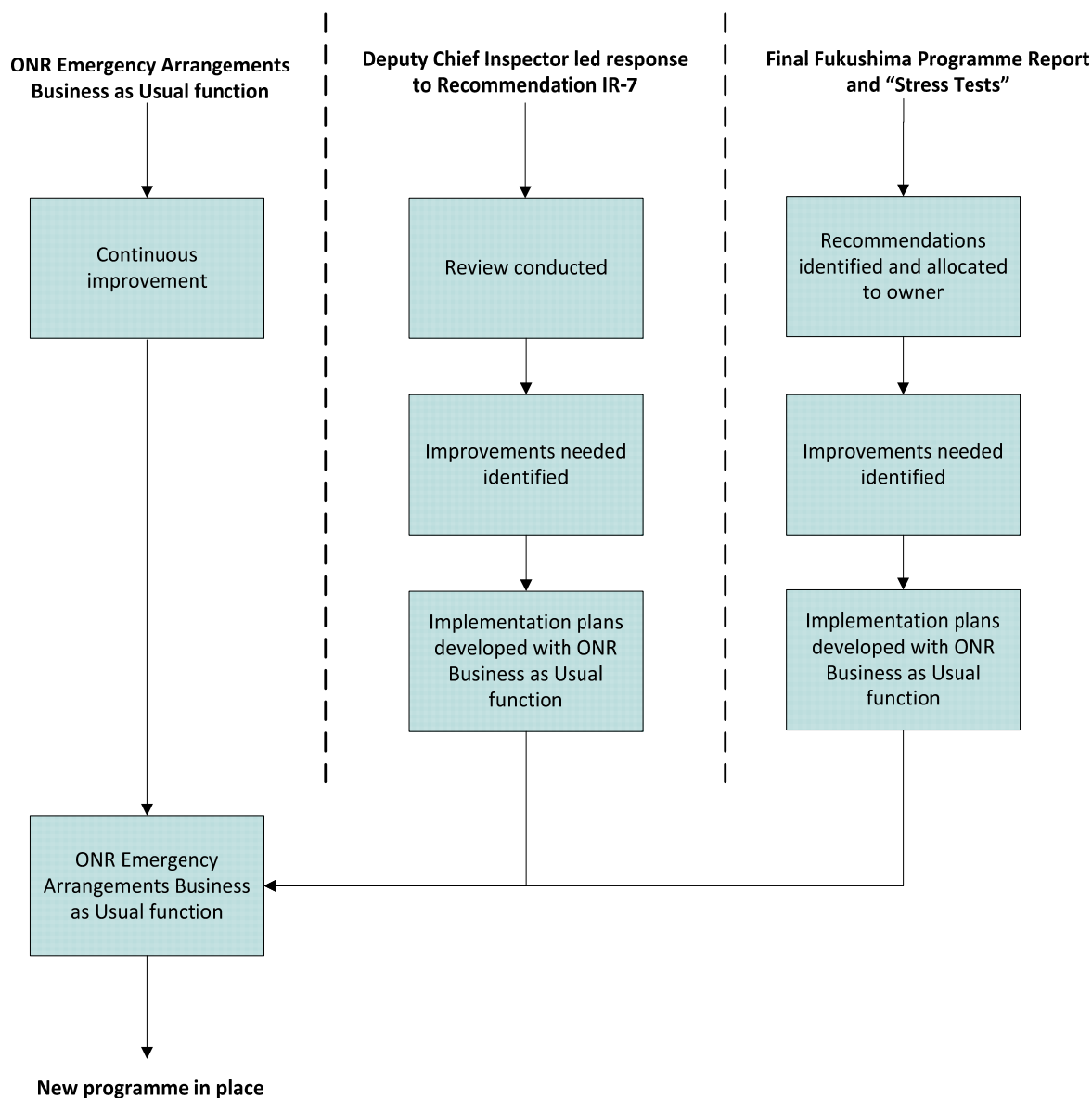


Figure 10: ONR Current Improvement Workstreams – Emergency Arrangements

- 594 The left-hand workstream of [Figure 10](#) is the on-going ONR business-as-usual function that is proactively continuing to improve through its existing links and engagement with NEPLG and other emergency arrangements stakeholders, and through working with our emergency arrangements training provider, Berwicks.
- 595 The right-hand workstream of [Figure 10](#) is aimed at identifying the lessons that have relevance to ONR's emergency arrangements function from many sources, such as our reports to the SoS, the Japanese report to IAEA Ref. [2](#)), the European Council "Stress Test" reports etc.
- 596 The middle workstream of [Figure 10](#) is a direct result of Recommendation IR-7 of our Interim Report. One of ONR's Deputy Chief Inspectors has been given the lead to work with our business-as-usual function to conduct a lessons learnt exercise specifically regarding our response during Fukushima (and other times when the ONR Redgrave Court Incident Centre has been operational, for example, during exercises) and our arrangements for responding to emergencies. This activity is

not yet complete, due to our view that our emergency arrangements function did respond well and we must ensure that whilst making improvements we do not undermine our good practices.

- 597 Regarding the timescales for the work illustrated in [Figure 10](#), we expect the left-hand workstream to be on-going; the right-hand workstream to close with the closure of the ONR Fukushima programme (with the production of our close-out “implementation report” - currently planned for 12 months time) and the middle workstream to identify the lessons and develop improvement implementation plans by the end of 2011.

Recommendations Relevant to the Nuclear Industry

- 598 We have received timely responses from all of the nuclear licensees and information that they have provided is to be published on our website, subject to the normal constraints regarding security etc. So, rather than reproducing those responses here, we have elected to provide a commentary on them and give views on whether we consider they represent an appropriate commitment at this stage.

EDF Energy

- 599 EDF Energy operates eight nuclear power stations in the UK and is aiming to build a new generation of nuclear plants at Hinkley Point in Somerset and Sizewell in Suffolk. EDF Energy is a subsidiary of the EDF Group, one of Europe’s largest energy generation groups.
- 600 EDF Energy provided an initial response (Ref. [40](#)) to the Interim Report recommendations which has subsequently been updated (Ref. [41](#)) to reflect progress, and to clarify some points following discussions with ONR.
- 601 The response from EDF Energy addresses both their Nuclear Generation (NG) business and their Nuclear New Build (NNB) business. Some aspects of the response are generic to both the NG and NNB businesses and are addressed within this section. Other aspects are specific to either the NG or NNB businesses and are considered under the appropriate headings, below. It is also noted that the response has been developed with, and is supported by, EDF Energy’s partner in nuclear operations, Centrica.
- 602 In their response EDF Energy acknowledges their support for the Interim Report recommendations and provides a commitment to thoroughly assess the lessons learnt and make appropriate improvements to their operations. The response also recognises, even at this early stage, that there will be a need to carefully assess and make appropriate changes in several key areas, including:
- continuing to improve open, transparent and trusted communications and relationships with key stakeholders;
 - enhancements to on-site resilience from the effects of major events;
 - provision of off-site emergency back-up equipment that can readily be connected to the plant;
 - the potential impact of abnormal natural events on local and national infrastructure; and
 - emergency planning arrangements to respond in extreme situations.
- 603 EDF Energy also indicates that it is looking to take a leading role in engagement with other stakeholders in the UK nuclear industry to ensure the most effective improvement for the industry

is achieved. Further to this, EDF Energy also makes it clear that, whilst they do not have the lead in responding to Recommendations IR-1 to IR-3 and IR-5 to IR-7, they have offered their support where appropriate. ONR supports such collaboration since it will help to ensure a consistent approach and maximise benefits across the UK nuclear industry.

- 604 It is also noted that EDF Energy recognises the synergy between the Interim Report recommendations and the “Stress Tests” requested by the Council of the European Union. This is discussed further below.

EDF Energy – Nuclear Generation Business

- 605 As noted above, EDF Energy’s NG business operates eight nuclear power stations in the UK. Seven of the power stations are AGRs, each of which has two reactors per station (Hinkley Point B, Heysham 1, Heysham 2, Torness, Hunterston B, Hartlepool and Dungeness B); the eighth is a single PWR (Sizewell B).
- 606 The initial response of EDF Energy NG to the events at Fukushima was to use its mandatory evaluation process to initiate a series of reviews of systems, processes and procedures at each of their sites. The aim of these is to confirm that systems essential to fuel cooling in an emergency situation in a within design basis event, including seismic and flooding scenarios, are correctly configured, lined up and in a suitable condition to be declared available / operable. These reviews included walk-downs around the sites using Suitably Qualified and Experienced Personnel (SQEP). A second mandatory evaluation of beyond design basis capability was also carried out.
- 607 These reviews are reported to have identified a number of enhancement options for further consideration aimed at increasing resilience in extreme events. ONR is currently carrying out inspections in relation to these reviews.
- 608 Beyond these initial reviews, EDF Energy NG has responded to each of the Interim Report recommendations using the pro forma described earlier. As requested by the Interim Report their initial response (Ref. [40](#)) to the recommendations was provided by 17 June 2011. A review of the response was carried out by ONR Inspectors to identify whether the response was adequate in terms of its scope and that appropriate timescales had been identified for progressing the recommendations. Following this review, a meeting was held with EDF Energy NG to clarify a number of points. Since then the response has been updated (Ref. [41](#)) primarily to include a section on progress, although the opportunity has also been taken to clarify the scope of the planned workstreams was appropriate based upon discussions with ONR.
- 609 The update (Ref. [41](#)) has also been reviewed by ONR. The response provides a commitment to address the full scope of the recommendations and highlights progress that has been made to date. With respect to progress ONR notes the following:
- Initial reviews, including focused walk-downs (Mandatory Evaluations), have been completed.
 - A dedicated team of about 40 people has been established, supported as necessary by other staff within EDF Energy, to respond to the events at Fukushima.
 - An EDF Energy, Magnox and Sellafield (EMS) steering group has been established to oversee the delivery of a number of jointly delivered recommendations.
 - EDF Energy is liaising with its parent company in France and sharing information to enable cross-fertilisation of ideas and options.

- With respect to Interim Report recommendations IR-1 and IR-2, a formal communication channel with the UK Government (DECC) has been established which enables a weekly discussion; this includes representatives from other UK operating companies.
- In response to Recommendation IR-3, EDF Energy is supporting NEPLG and has recently participated in a three-day workshop. Further workshops are planned in September and November 2011.
- Preparation is being made for an industry (current and future licensees) workshop in September 2011 with National Grid to develop terms of reference for a robustness review of off-site electrical supplies under severe hazard conditions.
- New severe accident modelling is being undertaken to confirm the understanding of accident sequences using modern methods.
- A number of potential enhancements to resilience have been identified for further consideration, including:
 - local flood protection to key plant items, e.g. raising of bund walls, use of local temporary defences, waterproofing of key doors;
 - provision of emergency back-up equipment which can be deployed quickly following any extreme event;
 - enhanced resilience of diesel generators;
 - enhanced resilience of coolant supplies;
 - use of passive temperature and pressure devices; and
 - introduction of satellite communications technology.

610 Through a number of discussions with EDF Energy NG, ONR understands that the Interim Report recommendations are being addressed through several workstreams which are also designed to address the “Stress Tests” requested by the Council of the European Union. ONR will be inspecting the scope and progress of these workstreams over the coming months to confirm that they will deliver appropriate outcomes on acceptable timescales. In this respect it is noted that EDF Energy NG intends to provide a progress update and work plan by October 2011. Noting that this aligns with completion and delivery of the “Stress Tests” reports, this is considered by ONR to be reasonable.

611 Overall, ONR considers that the EDF Energy NG response to the Interim Report recommendations provides an appropriate commitment to fully address the scope of the recommendations on a reasonable timescale. ONR will continue to inspect and monitor progress with respect to addressing the recommendations to ensure that these commitments are met.

EDF Energy – Nuclear New Build

612 The EDF Energy NNB programme is currently developing its design and safety justification for new UK EPR™ plants at Hinkley Point in Somerset and Sizewell in Suffolk. However, as highlighted by EDF Energy NNB, construction has not yet started and this provides an opportunity to learn from the event in Fukushima and to seek to provide a safer design, if reasonably practicable.

613 The response from EDF Energy NNB notes that the UK EPR™ design has been developed by the EDF Group and AREVA with the intent of making it available for use in the UK by any licensed operator.

As such, the UK EPR™ design is being assessed by ONR under the GDA process with EDF Group and AREVA acting as the Requesting Party. ONR has received a separate response from the Requesting Party under the GDA process and this is discussed further below.

614 A consequence of this approach is that the design and safety justification for new UK EPR™ plants at Hinkley Point and Sizewell may change either due to improvements to the generic design or improvements arising from site-specific changes. This is recognised by EDF Energy NNB who is working closely with the Requesting Party.

615 EDF Energy NNB has responded to each of the Interim Report recommendations using the pro forma described earlier. As requested by the Interim Report their initial response (Ref. [40](#)) to the Interim Report recommendations was provided by 17 June 2011. A review of the response was performed by ONR Inspectors to identify whether the response was adequate in terms of its scope and to confirm that appropriate timescales had been identified for progressing the recommendations. ONR's initial comments were provided to EDF Energy NNB with the aim of clarifying some aspects of the response. Since then the response has been updated (Ref. [41](#)), primarily to include a section on progress, but also to address ONR's comments where appropriate.

616 The update (Ref. [41](#)) has also been reviewed by ONR. The response provides a commitment to address the full scope of the recommendations and highlights progress that has been made to date. Some of this reflects that outlined above for EDF Energy NG, i.e. participation in the EMS steering group, communications with UK Government, and participation in the NEPLG and National Grid workshops. In addition to these, ONR notes the following:

- A number of reviews are in progress or planned to ensure lessons learnt are taken into account and potential enhancements to resilience identified; these include:
 - a review of the design basis and margins underway for the UK EPR™ regarding self-sufficiency of key supplies (power, water, diesel fuel, emergency equipment);
 - a review of flooding studies to be performed in September to identify any cliff-edge effects and potential resilience improvements;
 - a review of the assessment of external hazards report that is currently in production to be carried out in the light of events at Fukushima; and
 - a review of the resilience of control and instrumentation systems in progress.
- A number of potential enhancements to resilience are also currently being explored; these include:
 - diversity of the diesel generators;
 - flooding protection and hazard qualification of the diesel buildings, battery rooms and associated distribution equipment;
 - a larger water reservoir for make-up under severe accident conditions that is seismically qualified; and
 - increased battery capacity.

617 In their response EDF Energy NNB propose issuing a revised work plan and progress update in October 2011, which is consistent with that for developing the GDA resolution plans. In addition, quarterly progress meetings with ONR are proposed. Given the stage at which the EDF Energy nuclear new build programme is at, ONR considers this to be appropriate.

- 618 Overall, ONR considers that the EDF Energy NNB response to the Interim Report recommendations provides an appropriate commitment to fully address the scope of the recommendations. ONR will continue to inspect and monitor progress with respect to addressing the recommendations to ensure that these commitments are met.

Magnox

- 619 Magnox are responsible for two operating Magnox nuclear power stations (Oldbury and Wylfa), three nuclear power stations undergoing defuelling (Chapelcross, Dungeness A and Sizewell A) and five nuclear power stations undergoing decommissioning (Bradwell, Hinkley Point A, Berkeley, Trawsfynydd, Hunterston A).
- 620 The initial response of Magnox to the events at Fukushima was to use their mandatory assessment process to initiate a series of assessments at each of their generating and defuelling sites, which included re-evaluation of the potential effects of design basis and beyond design basis seismic and flooding events.
- 621 These reviews identified a number of areas of further work, for example to consider the adequacy of the beyond design basis trailers in terms of type and quantity of equipment, location and means of deployment, particularly in the event of significant national infrastructure damage.
- 622 Following these initial reviews Magnox has responded to each of the Interim Report recommendations using the pro forma described earlier. As requested by the Interim Report, their initial response (Ref. [42](#)) to the Interim Report recommendations was provided by 17 June 2011. A review of the response was carried out by ONR Inspectors to identify whether the response was adequate in terms of its scope and that appropriate timescales had been identified for progressing the recommendations. Comments arising from this review were provided to Magnox with the aim of clarifying a number of points. Since then the response has been updated (Ref. [43](#)) primarily to include a section on progress, but also to clarify the scope of the planned work based upon comments and discussions with ONR.
- 623 The update (Ref. [43](#)) has also been reviewed by ONR. In its response, Magnox confirms their agreement to the Interim Report recommendations and provides a commitment to address them and make appropriate improvements to their operations.
- 624 The response highlights that the work undertaken to date for Oldbury and Wylfa has identified a number of potential improvements which could enhance the resilience to various events, in particular extreme seismic or flooding events. Examples of the potential improvements highlighted by Magnox are:
- Enhanced protection of existing facilities to reduce the potential for damage.
 - Storage of existing on-site back-up equipment (e.g. spare pumps and pressure circuit sealing equipment) in diverse locations at various levels.
 - Provision of equipment to allow operators to move around site more easily and clear debris that may be present after an extreme hazard event.
 - Changes to the content, location and number of off-site emergency equipment trailers. For example, the equipment for Wylfa is held close to site but this is not the case for Oldbury. The intention is to provide appropriate equipment dedicated to the sites in secure, nearby locations
 - Improvements to the resilience of communications.

- 625 As part of their response to the Interim Report recommendations, Magnox has held a number of workshops (which have provided an input to the above) at which an ONR Inspector has been present as an observer. The first of these workshops was aimed at identifying potential improvements to increase resilience to extreme natural events at Wylfa power station. An equivalent workshop has also been held for Oldbury power station. The output from these workshops was then considered at a further workshop aimed at identifying those ideas that should be taken forward, those requiring further work, and those that should be rejected. ONR is also aware that further workshops are planned, for example, on the Wylfa dry fuel stores.
- 626 With respect to progress ONR also note the following:
- Initial reviews (mandatory assessments) have been completed.
 - A dedicated team has been established, supported as necessary by other staff within Magnox, to respond to the events at Fukushima.
 - An EMS steering group has been established to oversee the delivery of a number of jointly delivered recommendations.
 - With respect to Interim Report Recommendations IR-1 and IR-2, a formal communication channel with the UK Government DECC has been established, hosted by EDF Energy, which enables a weekly discussion including representatives from Magnox and other UK operating companies.
 - In response to Recommendation IR-3, Magnox is supporting NEPLG and have recently participated in a three-day workshop. Further workshops are planned in September and November 2011.
 - Preparation is being made for an industry (current and future licensees) workshop in September 2011 with National Grid to develop terms of reference for a robustness review of off-site electrical supplies under severe hazard conditions.
 - A critical review of the design basis flooding studies is being performed to identify any potential improvements needed to the design basis.
 - As noted above, a series of workshops are also in progress to consider potential improvements to resilience for beyond design basis events.
 - A walkdown by the Seismic Qualification User Group (which employs SQEPs) is planned for Oldbury and Wylfa.
 - A review of the Severe Accident Guidelines for all remaining phases of a site's lifecycle and covering the adequacy of training and exercising arrangements and external benchmarking is planned.
- 627 Through discussions with Magnox, ONR understands that the Interim Report recommendations are being addressed through a number of workstreams which are also designed to address the "Stress Tests" requested by the Council of the European Union. ONR will be inspecting the scope and progress of these workstreams over the coming months to confirm that they will deliver appropriate outcomes on acceptable timescales. In this respect it is noted that Magnox intends to provide a progress update and work plan by October 2011. Noting that this aligns with completion and delivery of the "Stress Tests" reports this is considered by ONR to be reasonable.
- 628 Overall, ONR considers that the Magnox response to the Interim Report recommendations provides an appropriate commitment to fully address the scope of the recommendations on a

reasonable timescale. ONR will continue to inspect and monitor progress with respect to addressing the recommendations to ensure that these commitments are met.

Horizon Nuclear Power

- 629 Horizon Nuclear Power is a joint venture between E.ON UK and RWE npower. Whilst Horizon Nuclear Power does not currently operate any nuclear power stations in the UK they are planning to deliver significant nuclear power station capacity in the UK in the future. As part of their plans, they have acquired sites at Wylfa on the island of Anglesey and at Oldbury-on-Severn in Gloucestershire, both of which are included in the list of sites included in the Government's Nuclear National Policy Statement. Given their plans, they have responded to the Interim Report recommendations.
- 630 As requested by the Interim Report, Horizon Nuclear Power provided an initial response (Ref. [44](#)) to the Interim Report recommendations by 17 June 2011. An update to this response has been provided in Ref. [45](#) which confirms that their original response remains valid.
- 631 A review of the response has been carried out by ONR Inspectors to identify whether its response is adequate in terms of its scope and commitment and that appropriate timescales have been identified for progressing the recommendations. In carrying out this review it was recognised that Horizon Nuclear Power are at a relatively early stage of their programme, in particular it is noted that they have not yet selected their preferred reactor technology.
- 632 In their response, Horizon Nuclear Power accepts all of the Interim Report recommendations and recognises that there are many lessons to be learnt from the events at Fukushima, especially for plants still at their design and development stage. As such, they highlight that the recommendations, together with other lessons that may emerge, will need to be embedded in the development, design, construction, commissioning, training, operation and decommissioning stages of the project lifecycle, and that they are at an early enough stage in their programme to address the recommendations in this manner. In particular, it is noted that Horizon Nuclear Power intends presenting a formal status report with respect to the recommendations as part of their Site Licence Application.
- 633 With respect to reactor technology, Horizon Nuclear Power is considering both the UK EPR™ design developed by the EDF Group and AREVA and the AP1000® developed by Westinghouse. Both of these designs are being assessed by ONR under the GDA process with EDF Group and AREVA acting as the Requesting Party for the UK EPR™ design and Westinghouse as the Requesting Party for the AP1000® design. ONR has received separate responses from the Requesting Parties under the GDA process and these are discussed further below.
- 634 In a number of its responses to recommendations (e.g. Recommendation IR-14 relating to the design of spent fuel ponds) Horizon Nuclear Power notes that the Requesting Parties have been approached to outline their proposals to address the recommendations and that they understand that the Requesting Parties will be addressing such aspects as part of the GDA process. Although such aspects will be addressed as part of the GDA process, it is also noted that Horizon Nuclear Power provides a commitment to ensure that whichever reactor design is selected it will have been fully assessed against the Interim Report recommendations. This will also be monitored by ONR to ensure such recommendations are fully addressed.
- 635 A number of the responses (e.g. Recommendation IR-13 relating to plant and site layout) also refer to the fact that external hazard assessments are a key piece of early work in the programme for

both sites and that they are well underway for Wylfa and are taking account of extreme events. This work is the subject of on-going discussions with ONR and we will continue to inspect and monitor progress to ensure that such hazard assessments provide an appropriate basis for design decisions.

- 636 With respect to emergency arrangements, ONR notes that the response from Horizon Nuclear Power recognises the need to consider such aspects as the need for centrally held or local to site logistical support, effective communication systems and remote instrumentation and that the timing of the development of the emergency arrangements will be set out in the Site Licence Application.
- 637 It is also noted that Horizon Nuclear Power indicate that it is keen to learn from others in the UK nuclear industry and highlights that they are engaged with the SDF and the NEPLG to help ensure that they are engaged both with current good practice and emerging thinking. Such collaboration is supported by ONR since it will help to ensure a consistent approach and maximise benefits across the UK nuclear industry.
- 638 Whilst at an early stage in their programme, ONR considers that the Horizon Nuclear Power response to the Interim Report recommendations provides an appropriate commitment to fully address the scope of the recommendations on a timescale commensurate with their position as a future potential licensee. ONR will continue to inspect and monitor progress with respect to addressing the recommendations to ensure that these commitments are met.

NuGeneration Limited

- 639 NuGeneration Limited (NuGen) is a consortium of GDF Suez, Scottish and Southern Energy and Iberdrola which aims to develop and build a new nuclear power station in the UK. Whilst NuGen does not currently operate any nuclear power stations in the UK, they have acquired a site near Sellafield in west Cumbria which is included in the list of sites identified in the Government's Nuclear National Policy Statement. Whilst at a very early stage in their programme, given their intentions they have provided a response to the Interim Report recommendations.
- 640 As requested by the Interim Report, NuGen provided an initial response (Ref. [46](#)) to the Interim Report recommendations by 17 June 2011. An update to this response has been provided (Ref. [47](#)) which confirms that their original response remains valid.
- 641 A review of the response has been carried out by ONR Inspectors to identify whether the response is adequate in terms of its scope and commitment and that appropriate timescales have been identified for progressing the recommendations. In carrying out this review it was recognised that NuGen are at a very early stage of their programme.
- 642 In their response, NuGen confirms its support for the Interim Report recommendations and recognises the importance of learning lessons from the events at Fukushima. They also note that whilst they are at an early phase of the development process including developing safety and company governance control, technology selection, site assessment and regulatory processes, they provide their assurance that national and international good practices will be considered and applied as appropriate.
- 643 In terms of reactor technology, NuGen is considering both the UK EPR™ design developed by the EDF Group and AREVA and the AP1000® developed by Westinghouse. Both of these designs are being assessed by ONR under the GDA process, with EDF Group and AREVA acting as the Requesting Party for the UK EPR™ design and Westinghouse as the Requesting Party for the

AP1000[®] design. ONR has received separate responses from the Requesting Parties under the GDA process and these are discussed further below.

- 644 For those recommendations which may, at least in part, be addressed through the GDA process, NuGen recognises that they will need to work with the Requesting Parties to ensure an appropriate outcome. Similarly, they also recognise that they will need to address the site specific aspects, for example through flooding studies that they will carry out for their site near Sellafield in west Cumbria. ONR also notes NuGen's offer to participate in any initiative that UK agencies propose with respect to emergency arrangements. Whilst at an early stage of development, these commitments are acknowledged by ONR and considered appropriate at this stage. Clearly, as recognised by NuGen, being at such an early stage in their development provides a valuable opportunity to ensure that the maximum benefit is taken from the lessons learnt from the events at Fukushima.
- 645 With respect to timescales for addressing the recommendations, NuGen reports that given the current status of their development it is not yet possible to provide specific dates, but that they envisage that the issues and actions associated with the recommendations will form part of the application process for a site licence. This position is acknowledged by ONR.
- 646 Whilst at a very early stage in their programme ONR considers that the NuGen response to the Interim Report recommendations provides an appropriate commitment to fully address the scope of the recommendations on a timescale commensurate with their position as a future potential licensee. ONR will continue to inspect and monitor progress with respect to addressing the recommendations to ensure that these commitments are met.

Generic Design Assessment

- 647 As stated earlier in this report, a response was requested to the Interim Report on the events at Fukushima from both Requesting Parties involved in the UK GDA process for new reactor designs. Responses were subsequently received from EDF Group and AREVA (Ref. [48](#)) for the UK EPR™ and Westinghouse (Ref. [49](#)) for the AP1000[®] new reactor designs.
- 648 Within the GDA process a GDA Issue was raised on both Requesting Parties by ONR and EA to provide a Resolution Plan to address the lessons learnt from Fukushima. Additionally, in our GDA quarterly report (see www.hse.gov.uk/newreactors/index.htm) ONR and the Environment Agency stated that both Requesting Parties have given a commitment to provide Resolution Plans for all of their GDA Issues (raised in the GDA process) by the autumn 2011, including for the Fukushima GDA Issue (see www.hse.gov.uk/newreactors/index.htm). ONR has committed to consider the adequacy of these Resolution Plans, and when we judge them to be credible, we will publish them. Once all the Resolution Plans are published, along with the Safety Security and Environmental Reports, the Design References and Master Submission Lists, we will consider providing an interim Design Acceptance Confirmation (iDAC) and interim Statement of Design Acceptability (iSODA).

Sellafield

- 649 Sellafield Limited has provided an initial response (Ref. [50](#)), using the agreed pro forma, to the Interim Report recommendations by the requested date (17 June 2011). A subsequent progress report has also been submitted (Ref. [51](#)) again by the requested date (31 July 2011).

- 650 ONR has established regular liaison with the Sellafield Limited Resilience Project team which is tasked to progress the work programmes that have been established to address the ONR Interim Report recommendations and European Council “Stress Tests” requirements. These ONR / Sellafield Limited discussions have provided, and will continue, to provide an opportunity for ONR Specialist Inspectors (with the support of Environment Agency Inspectors where appropriate) to assess the detailed findings of the on-going review and analysis work currently being carried out by Sellafield Limited.
- 651 Sellafield Limited has developed a Resilience Evaluation Process which is currently being applied to the major facilities across the Sellafield site and the supporting site utilities systems. This review will analyse various accident scenarios, durations and “cliff-edge” effects and seek to identify robust measures to reduce dependencies within systems and additional effective mitigating / curtailment systems.
- 652 The Sellafield Limited initial and update responses (Refs [50](#) and [51](#)) reflect the fact that the various work programmes being undertaken to address the recommendations have yet to be completed and thus the responses do not detail recommended improvements etc. It is evident from ONR / Sellafield Limited interactions that Sellafield Limited is now starting to identify a number of improvements and additional contingency measures for facilities across the site and the supporting infrastructure systems. For many of the older legacy facilities, it has been recognised by Sellafield Limited and ONR that the facilities are not as robust as the newer facilities built to modern design standards, and hence the main focus for the site must remain the retrieval of the radioactive inventory from these facilities and the processing of the material into safer waste forms. In the meantime, contingency measures are put in place.
- 653 Sellafield Limited has been working closely with EDF Energy NG and Magnox Limited to ensure that a consistent best practices approach is adopted for the analysis reviews and suggested improvements.
- 654 Overall, ONR considers that Sellafield Limited responses to the ONR Interim Report recommendations demonstrate that Sellafield Limited has made an appropriate commitment to progress work activities to address the recommendations in the ONR Interim Report

Restoration Sites

- 655 Dounreay, Harwell and Winfrith are three nuclear licensed sites undergoing programmes of decommissioning and site restoration. These sites are operated by site licence companies on behalf of the NDA. The three restoration site licensees developed their respective responses according to a standard pro forma developed by the SDF. In their responses, the licensees acknowledge their support for the Interim Report recommendations
- 656 The Dounreay site is operated by DSRL. There are no operational reactors on the site, nor holdings of heat-generating materials that require active cooling. DSRL has stated that there are no operational facilities or facilities undergoing decommissioning that require operator intervention to maintain their basis of safety.
- 657 DSRL provided a comprehensive initial response (Ref. [52](#)) to the Interim Report recommendations, and subsequent to that an update on progress towards addressing relevant recommendations (Ref. [53](#)). DSRL does not postulate any credible energetic release scenario leading to widespread dispersion of material beyond the local environment other than the potential for materials to be

washed-out to sea. Dounreay facilities are designed to migrate to a passively safe state and do not have safety-related dependence upon on-site or off-site services.

- 658 The update highlights progress that has been made to date. ONR notes the following:
- Eight out of the 25 recommendations warrant further work to be undertaken by DSRL.
 - DSRL has undertaken a review to establish any reasonably practicable improvements to improve resilience to flooding.
 - DSRL is to review resilience of facilities that rely on inert gas to long-term unavailability (>7 days).
 - DSRL intends to review ventilation arrangements for operational facilities that facilitate decommissioning, and the designs for facilities yet to be constructed.
 - Command and control arrangements, particularly for long-lived events, are under review and DSRL plans to test these arrangements. DSRL has engaged closely with the Nuclear Emergency Arrangements Forum.
 - DSRL has begun a review of its Hazard Identification and Risk Evaluation (HIRE) report (which supports its REPIR submission) in the context of resilience of existing arrangements to long-term disruption to the site.
- 659 Overall ONR considers that the DSRL response to the Interim Report recommendations provides an appropriate commitment to fully address the scope of relevant recommendations, and on a reasonable timescale. ONR will continue to inspect and monitor progress with respect to addressing the recommendations to ensure that these commitments are met.
- 660 Research Sites Restoration Limited (RSRL) operates the licensed facilities at Harwell and Winfrith. Licensed facilities on these sites are undergoing decommissioning and care and maintenance activities. RSRL states that research reactors have been de-fuelled so do not have the potential to lead to a long-term severe accident. RSRL's response to the Interim Report recommendations (Ref. [54](#)) acknowledges the need to review the resilience of its safety systems and supplies to extreme events. RSRL further notes its intention to liaise closely with the SDF to ensure consistency of approach.
- 661 Overall, ONR considers that the RSRL response to the Interim Report recommendations provides an appropriate commitment to fully address the scope of relevant recommendations, and on a reasonable timescale. ONR will continue to inspect and monitor progress towards addressing the recommendations to ensure that these commitments are met.

Commercial Sites

- 662 URENCO UK Limited operates centrifuge enrichment facilities at the Capenhurst nuclear licensed site. The UUK group operates a number of centrifuge enrichment facilities across the world, according to a variety of regulatory requirements. The licensee's response to the Interim Report recommendations (Ref. [55](#)) states that no coolant or external power supply is needed to sustain the containment of uranium hexafluoride process gas. Disruption to electrical power supply during centrifuge operation would result in fail-safe shut down. UUK further dismisses flooding as a significant hazard due to the topography of the region. ONR notes UUK's intention to review the potential effect of wide-spread off-site disruption, and necessary enhanced training within a review of its emergency plans. Overall, ONR considers that the UUK response to the Interim Report

recommendations provides an appropriate commitment to adequately address the scope of relevant recommendations, and on a reasonable timescale.

- 663 Springfields Fuels Limited (SFL) operates the Springfields nuclear licensed site undertaking manufacture of uranium hexafluoride, oxide fuels for AGR and LWR reactors, residue processing and decommissioning activities. SFL's response to the Interim Report recommendations (Ref. [56](#)) states that SFL's facilities are designed to fail-safe in the event of power failure, with no dependency on continuing electricity supply for nuclear safety. SFL further states that the site has on-site generation capability, so is not reliant upon the National Grid. SFL does not consider the site to be vulnerable to flooding due to the region's topography and does not require active cooling to sustain nuclear safety. ONR notes SFL's intention to review its emergency planning assumptions, controls and contingency arrangements for prolonged severe accidents that involve widespread off-site disruption. ONR considers that the UUK response to the Interim Report recommendations provides an appropriate commitment to adequately address the scope of relevant recommendations.
- 664 The Low Level Waste Repository nuclear licensed site, located adjacent to the Sellafield site in west Cumbria, is operated by LLW Repository Limited. LLWR's response to the Interim Report (Ref. [57](#)) indicates that given the low level of hazards on the site, there is no reliance on complex control systems or instrumentation, nor any reliance on continuing power supplies to maintain nuclear safety. LLWR states that the site's geography ensures that extreme rainfall will not affect on-site facilities, but proposes to carry out further quantification of resilience to possible tsunamis to provide more confidence. LLWR does not consider there to be any requirement to seismically qualify its facilities due to the low consequence inventory. ONR notes LLWR's proposal to confirm adequacy of safety assessments for extreme events and subsequent fire, and the site's resilience to them, to confirm robustness of the site's emergency plan for prolonged loss of service under extreme scenarios. ONR acknowledges LLWR's assumption that in the event of an extreme event affecting the local area, resource would be focused upon the adjacent Sellafield site. ONR considers that the LLWR response to the Interim Report recommendations provides an appropriate commitment to fully address the scope of relevant recommendations.
- 665 Studsvik Metal Recycling Facility in Cumbria is a low hazard facility dealing with small quantities of low activity material in batch-wise operations. The licensee states (Ref. [58](#)) that the majority of the Interim Report recommendations do not apply to the site. ONR acknowledges and agrees with this position. Studsvik UK Limited has not identified, in its response, the detail of the licensee's review but ONR is satisfied with the proposed timescale to address relevant recommendations.
- 666 Imperial College operates a low power research reactor at Ascot. ONR notes that the reactor hazards are limited to on-site and that it is at the early stages of a decommissioning programme. The majority of Interim Report recommendations will have limited impact on the facility. Nevertheless, Imperial College has appropriately committed itself to reviewing the Interim Report recommendations (Ref. [59](#)). ONR notes that Imperial College does not intend to undertake any further review on flooding due to the site's location and geography and acknowledges the licensee's proposal to review safety-related on- and off-site supplies. ONR is satisfied with the proposed timescale to address relevant recommendations.
- 667 GE Healthcare Limited (GEHC) has three nuclear licensed sites in the UK; the Grove Centre at Amersham; the Maynard Centre at Cardiff and a building at Harwell. GEHC operations centre on the manufacture of radiopharmaceutical products. GEHC's response to the Interim Report (Ref. [60](#)) states that the Grove Centre is currently implementing its decommissioning plan that will result in decreased ILW inventory for on-site storage. The Maynard Centre is also undergoing

decommissioning and continues to store ILW waste, with plans to reduce this in coming years. GEHC's former waste packaging facility and source manufacture operations at Harwell have ceased, and activities now relate to post-operational clean-out. None of these facilities require off-site emergency plans, justified in GEHC's April 2011 REPPIR submission to ONR. GEHC states that severe flooding on its Amersham and Harwell sites is not credible; GEHC further asserts that whilst flooding at its Cardiff site could occur once every hundred years, containment is resilient to such events. GEHC considers its sites to be self-sufficient with respect to maintaining site safety, without reliance on off-site infrastructure. ONR acknowledges GEHC's proposal to review multiple concurrent events between facilities on its sites to confirm arrangements for response to extreme events are adequate. ONR is satisfied with the proposed timescale to address relevant recommendations.

Atomic Weapons Establishment, Aldermaston and Burghfield

- 668 AWE provided an initial response (Ref. [61](#)) to the Interim Report recommendations by the requested date, which encompassed both of their operational sites. AWE provided assurance that they support the UK review process for ensuring the lessons learnt are applied.
- 669 It is noted that AWE has concluded a ten-year periodic review of safety which required comparing their existing infrastructure and management systems against modern standards. AWE acknowledges that improvements have been identified and ONR will monitor AWE's progress in its implementation of improvements.
- 670 Overall, ONR considers that the AWE response to the Interim Report recommendations demonstrates that AWE has made an appropriate commitment to progress work activities to address the recommendations.

Nuclear Fuel Production Plant and Neptune Reactor, Derby, Derbyshire

- 671 RRMPOLE provided initial responses (Ref. [62](#)) to the Interim Report recommendations by the requested date, which encompassed both of their operational facilities.
- 672 It is noted that RRMPOLE will conclude a periodic review of safety in 2012. ONR expects that the latest Environment Agency flood modelling data will be included in this review. Overall, ONR considers that the RRMPOLE responses to the Interim Report recommendations demonstrate that RRMPOLE has made an appropriate commitment to progress work activities to address the recommendations.

Devonshire Dock Complex, Barrow-in-Furness

- 673 BAESM provided initial response (Ref. [63](#)) to the Interim Report recommendations by the requested date.
- 674 BAESM has stated that for the majority of responses to the Interim Report recommendations will be incorporated within the periodic review of safety, which is due in 2014. ONR considers that an earlier response to the Interim Report recommendations is appropriate and correspondence with BAESM on this matter has been initiated.

Devonport Royal Dockyard, Plymouth

- 675 DRDL provided initial response (Ref. [64](#)) to the Interim Report recommendations by the requested date.
- 676 Whilst we are content with many aspects of the response, we are seeking further clarification of some areas. It has not been possible to do this on a timescale that allowed this clarification to be included within this report but an update will be provided in ONR's future implementation report.
- 677 Overall, ONR considers that the DRDL responses to the Interim Report recommendations demonstrate that DRDL has made an appropriate commitment to progress work activities to address the recommendations.

Rosyth Royal Dockyard

- 678 RRDL provided initial response (Ref. [65](#)) to the Interim Report recommendations by the requested date.
- 679 Overall, ONR considers that the RRDL responses to the Interim Report recommendations demonstrate that RRDL has made an appropriate commitment to progress work activities to address the recommendations.

Progress on European Council "Stress Tests"

- 680 Following the Japanese earthquake and tsunami of 11 March 2011 and the subsequent events at the Fukushima-1 site, the European Nuclear Safety Regulatory Group (ENSREG) has defined a set of "Stress Tests" to be carried out in European Union member states for NPPs in operation or being constructed. These were adopted by the European Council on 26 May 2011.
- 681 Operation is defined as any NPP site where fuel is still on-site. Each member state will produce an interim and final national report which will be prepared based on licensee reports. The Final Report will be submitted to the European Council and will be subject to a peer review process to be organised by ENSREG. The ENSREG specification for the "Stress Tests" is reproduced in [Annex J](#) of this report.
- 682 In the UK, the "Stress Tests" are also to be applied to non-NPP licensed nuclear installations. However, the reporting arrangements (which do not require submission to the European Council or the peer review) are yet to be finalised, although the principles of licensee reports and an ONR summary report are established. ONR will report the outcome of these tests in ONR's future implementation report.
- 683 The timescales for the "Stress Tests" are given in the table below:

Date	European "Stress Tests" (EST)
1 June 2011	ONR initiates licensee "Stress Tests" (NPP and non-NPP)
15 August 2011	NPP licensees submit Progress Reports (these have been received)
15 September 2011	ONR submits UK National Progress Report on NPPs
To be determined	Licensees submit non-NPP "Stress Tests" Progress Reports

Date	European “Stress Tests” (EST)
To be determined	ONR produces UK National Progress Report for non-NPP “Stress Tests”
31 October 2011	NPP licensees submit Final Reports
31 December 2011	ONR produces final UK National Report on NPPs
To be determined	ONR produces Final non-NPP Report
April 2012	European peer review output on NPP National Reports

684 The outcome of the “Stress Tests”, our assessment of them, and the output from the peer review process are, along with the recommendations in this report, all expected to help shape and influence the way in which learning from Fukushima is captured and implemented for UK nuclear installations.

Other Stakeholder Submissions

- 685 To inform the Interim and Final Reports on the lessons to be learnt from the nuclear accident at Fukushima, HM Chief Inspector of Nuclear Installations invited stakeholders to submit any evidence which they consider may help inform or support the development of the reports. ONR received 73 submissions for the Interim Report, and 53 for the Final Report from a wide range of stakeholders, including non-governmental organisations, nuclear industry representatives, Government departments, other regulators, international nuclear organisations, academics and members of the public. The range of comments was broad, covering seismic activity, emergency planning arrangements and the scope of the report. A number of people also took the opportunity to express their views on nuclear power.
- 686 Where the submissions were relevant to the work of HM Chief Inspector of Nuclear Installations, in producing the Interim and Final Reports for example focused on the cause or progression of the accident, the behaviour of the plant or personnel, management of the emergency, and suggestions for lessons to be learnt, the submissions were reviewed in more detail by relevant ONR Inspectors. Any new information was used to inform the Interim and Final reports.
- 687 The submissions are available on the ONR website at:
www.hse.gov.uk/nuclear/fukushima/submissions/index.htm.

EXTERNAL TECHNICAL ADVICE

Technical Advisory Panel

688 HM Chief Inspector of Nuclear Installations asked for a Technical Advisory Panel to be formed in order to provide timely and well founded independent technical advice relevant to this report. As well as advising on the scope of the report, the TAP was also requested to identify gaps in the technical review of the Fukushima event (and propose measures to close them) and to peer review the individual contributions to the report for clarity, accuracy and technical content.

689 Nominations for TAP membership were sought from a wide range of stakeholders. The nominees were to be independent technical advisors, not representing their own stakeholder community. The individuals that had been nominated were then invited by ONR to become a member of the TAP and were also advised at this time regarding the Code of Conduct TAP members were expected to comply with. The Code of Conduct was as follows:

Code of Conduct

Members of the Technical Advice Panel and their nominated representatives must comply with the following code of conduct. They should:

- *conduct themselves with integrity and honesty and not misuse their position on the Technical Advice Panel or information acquired in the course of their participation to further their personal interests or those of others;*
- *not receive benefits of any kind which others might reasonably see as compromising their personal judgement or integrity. They should not, without authority, disclose information which has been communicated in confidence or received in confidence from others. Discussions and advice provided to the Chief Inspector of Nuclear Installations will remain confidential whilst the Technical Advice Panel is operational. However, full details of this advice may be released later under the Government's principles of freedom of information;*

You are of course entitled to talk to the media as an expert in your own right while maintaining membership of the Technical Advice Panel, but you must not:

- *claim that your views are representative of the Technical Advice Panel and / or its other members in any way, or allow that impression to be created;*
- *divulge details of discussions that happened in the Technical Advice Panel, or the outcomes of those discussions;*
- *pass on any information which you would not have had, had you not been a member of the Technical Advice Panel.*

690 Invitations for TAP membership were accepted by the following people:

Edmund Booth – Royal Academy of Engineering
John Earp – Consultant, Nuclear Institute
Jim Gemmill – SEPA
Mark Gorry – Safety and Technical Director, EDF
Robin Grimes – Imperial College London
Paul Haworth – National Nuclear Laboratories
Kevin Horsburgh – National Oceanography Centre

Joe McHugh – Head of Radioactive Substances Regulation, Environment Agency

Anastasios Zodiates – Radiation Protection Consultant, Prospect Union

- 691 During the development of this report, TAP members met three times: 6 May 2011, 1 August 2011 and 2 September 2011. TAP members were also provided with the opportunity to meet individually with the ONR authors of technical sections of this report. They were also sent draft papers for their review.
- 692 The advice provided by the TAP covered human and organisational factors, earthquake and tsunami, seismic vulnerability, radiological protection, reactor safety, nuclear engineering, nuclear fuel, accident analysis, emergency response, flood risk, environmental monitoring and off-site hazards.
- 693 The advice was valuable and was taken into consideration during the writing of the report; however the conclusions and recommendations are ONR's own.

INTERNATIONAL ATOMIC ENERGY AGENCY MISSION TO JAPAN

Summary of Mission to Japan

- 694 By agreement with the government of Japan, IAEA conducted a fact-finding mission. The (UK) HM Chief Inspector of Nuclear Installations and Executive Head of ONR was asked by IAEA to lead this mission, which was undertaken from 24 May to 2 June 2011. The main aim of the mission was to identify lessons so that the worldwide nuclear community could learn from the accident at Fukushima.
- 695 The mission comprised a number of international experts and support from IAEA as follows:
- WEIGHTMAN, Michael – HSE ONR, UK, Team Leader
 - JAMET, Philippe – ASN, France, Deputy Team Leader
 - LYONS, James E. – IAEA, NSNI, Director
 - SAMADDAR, Sujit – IAEA, NSNI, Head, ISCC
 - CHAI, Guohan – People’s Republic of China
 - CHANDE, S. K. – AERB, India
 - GODOY, Antonio – Argentina
 - GORYACHEV, A. – NIIAR, Russian Federation
 - GUERPINAR, Aybars – Turkey
 - LENTIJO, Juan Carlos – CSN, Spain
 - LUX, Ivan – HAEA, Hungary
 - SUMARGO, Dedik E. – BAPETEN, Indonesia
 - SUNG, Key Yong – KINS, Republic of Korea
 - UHLE, Jennifer – US NRC, USA
 - BRADLEY, Edward E. – IAEA, NEFW, RRS
 - WEBB, Gregory Paul – IAEA, MTPI
 - PAVLICEK, Petr – IAEA, MTPI
 - NAMMARI, Nadia – IAEA, NSNI
- 696 During the time in Japan, the mission held many discussions with Japanese government departments, the Japanese nuclear industry and Japanese regulators. Several of these discussions were held with a heavy media presence and those that were not were subject to intense subsequent press interest. It should be noted that other important opportunities for the mission were the ability to visit the affected nuclear power plant facilities, Fukushima-1, Fuhushima-2 and Tokai, and to talk to the facility staff and managers that were present during the accident and the aftermath. This enabled the findings of the mission to be generated with first-hand knowledge of the context of the accident and the scenario facing the operators.
- 697 The mission conducted a preliminary assessment during their time in Japan and produced an immediate summary report, which was handed to the government of Japan at the end of the mission. This report indicated that the mission had received excellent co-operation from all during their time in Japan. It also set out the mission’s immediate assessment of relevant conclusions and recommendations in three main areas: external hazards; severe accident management; and emergency preparedness.

698 A fuller, more considered, report was generated by IAEA for discussion at its Ministerial Conference 20–24 June 2011. This report was fully consistent with the immediate summary report but added more context and clarified some of the conclusions and lessons.

Key Conclusions of the Mission

699 The conclusions, stated in Ref. [3](#), were as follows:

Conclusion 1: *The IAEA Fundamental Safety Principles provide a robust basis in relation to the circumstances of the Fukushima accident and cover all the areas of lessons learned from the accident.*

Conclusion 2: *Given the extreme circumstances of this accident the local management of the accident has been conducted in the best way possible and following Fundamental Principle 3.*

Conclusion 3: *There were insufficient defence-in-depth provisions for tsunami hazards. In particular:*

- *although tsunami hazards were considered both in the site evaluation and the design of the Fukushima Dai-ichi [Fukushima-1] NPP as described during the meetings and the expected tsunami height was increased to 5.7 m (without changing the licensing documents) after 2002, the tsunami hazard was underestimated;*
- *thus, considering that in reality a “dry site” was not provided for these operating NPPs, the additional protective measures taken as result of the evaluation conducted after 2002 were not sufficient to cope with the high tsunami run-up values and all associated hazardous phenomena (hydrodynamic forces and dynamic impact of large debris with high energy);*
- *moreover, those additional protective measures were not reviewed and approved by the regulatory authority;*
- *because failures of Structures, Systems and Components (SSC) when subjected to floods are generally not incremental, the plants were not able to withstand the*
- *consequences of tsunami heights greater than those estimated leading to cliff-edge effects; and*
- *severe accident management provisions were not adequate to cope with multiple plant failures.*

Conclusion 4: *For the Tokai Dai-ni and Fukushima Dai-ni [Fukushima-2] NPPs, in the short term, the safety of the plant should be evaluated and secured for the present state of the plant and site (caused by the earthquake and tsunami) and the changed hazard environment. In particular, if an external event Probabilistic Safety Assessment (PSA) model is already available, this would be an effective tool in performing the assessment.*

Short term immediate measures at Fukushima Dai-ichi [Fukushima-1] NPP need to be planned and implemented for the present state of the plant before a stable safe state of all the units is reached. Until that time the high priority measures against external hazards need to be identified using simple methods in order to have a timely plan. As preventive measures will be important but limited, both on-site and off-site mitigation measures need to be included in the plan. Once a stable safe state is achieved a long term plan needs to be prepared that may include physical improvements to SSCs as well as on-site and off-site emergency measures.

Conclusion 5: An updating of regulatory requirements and guidelines should be performed reflecting the experience and data obtained during the Great East Japan Earthquake and Tsunami, fulfilling the requirements and using also the criteria and methods recommended by the relevant IAEA Safety Standards for comprehensively coping with earthquakes and tsunamis and external flooding and, in general, all correlated external events. The national regulatory documents need to include database requirements compatible with those required by IAEA Safety Standards. The methods for hazard estimation and the protection of the plant need to be compatible with advances in research and development in related fields.

Conclusion 6: Japan has a well organized emergency preparedness and response system as demonstrated by the handling of the Fukushima accident. Nevertheless, complicated structures and organisations can result in delays in urgent decision making.

Conclusion 7: Dedicated and devoted officials and workers, and a well organized and flexible system made it possible to reach an effective response even in unexpected situations and prevented a larger impact of the accident on the health of the general public and facility workers.

Conclusion 8: A suitable follow up programme on public exposures and health monitoring would be beneficial.

Conclusion 9: There appears to have been effective control of radiation exposures on the affected sites despite the severe disruption by the events.

Conclusion 10: The IAEA Safety Requirements and Guides should be reviewed to ensure that the particular requirements in design and severe accident management for multi-plant sites are adequately covered.

Conclusion 11: There is a need to consider the periodic alignment of national regulations and guidance to internationally established standards and guidance for inclusion in particular of new lessons learned from global experiences of the impact of external hazards.

Conclusion 12: The Safety Review Services available with the IAEA's International Seismic Safety Centre (ISSC) would be useful in assisting Japan's development in the following areas:

- External event hazard assessment;
- Walkdowns for plants that will start up following a shut down; and
- Pre-earthquake preparedness.

Conclusion 13: A follow-up mission including Emergency Preparedness Review (EPREV) should look in detail at lessons to be learned from the emergency response on and off the site.

Conclusion 14: A follow-up mission should be conducted to seek lessons from the effective approach used to provide large scale radiation protection in response to the Fukushima accident.

Conclusion 15: A follow-up mission to the 2007 Integrated Regulatory Review Service (IRRS) should be conducted in light of the lessons to be learned from the Fukushima accident and the above conclusions to assist in any further development of the Japanese nuclear regulatory system.

Lessons Learnt

700 We endorse the conclusions and lessons of the mission and are ready to play an active role in any follow up work undertaken by IAEA.

Impact of the IAEA Mission's Lessons and Conclusions on the UK Situation

- 701 The IAEA mission report was discussed at the IAEA Ministerial Conference in June 2011. This conference included three working sessions:
- Preliminary Assessment of the Accident at TEPCO's Fukushima Dai-ichi [Fukushima-1] Nuclear Power Stations and Actions for Safety Improvements.
 - Emergency Preparedness and Response.
 - The Global Nuclear Safety Framework.
- 702 HM Chief Inspector of Nuclear Installations and Executive Head of ONR was the Chairperson of Working Session 1.
- 703 The main outcome of this conference was the requirement for IAEA to generate an action plan based on the working session chairperson's summaries. At the time of writing this report, this action plan is in the process of being drafted for discussion and approval at the IAEA General Conference, 19–23 September. It is expected that this action plan will be placed in the public domain by IAEA but the timescales of this preclude further discussion in this report. It is also expected that this action plan will contain actions for IAEA member states, which includes the UK.
- 704 Rather than wait for the action plan, ONR has taken account of the IAEA mission's conclusions in this report and we have also considered all of the lessons from the IAEA mission report and taken them into account in forming our own views on the impact on the UK situation. Indeed along with the Japanese government's report to IAEA, the mission report is one of the main inputs to our work in compiling this report.
- 705 [Annex H](#) gives a brief summary of where the IAEA mission lessons are covered in this report.

LESSONS LEARNT IN THE REPORT OF THE JAPANESE GOVERNMENT TO THE INTERNATIONAL ATOMIC ENERGY AGENCY

- 706 The report of the Japanese government (Ref. [2](#)) is a key source of information that we have used to produce our own report. As well as factual information, the Japanese report provides state of the art analyses that give valuable insights into the likely progression of the severe accidents (see [Annex L](#)) and Section XII of Ref. [2](#) contains a detailed list of the lessons they have learnt so far.
- 707 Amongst the lessons in Section XII of Ref. [2](#), the Japanese recognise that the major cause of the accident was that the design against tsunami was inadequate and the inability to secure necessary power supplies was a key contributor to the accident progression.
- 708 The Japanese report lessons also recognise the need for clarity in the administration of nuclear safety in Japan so that there is certainty over where responsibility for ensuring public safety in a nuclear emergency lies.
- 709 The lessons learnt also reflect on missed opportunities noting that they had not utilised PSA effectively in the past and noting that it needs to be used to a much greater extent to develop improvements and inform effective severe accident management measures.
- 710 It is fair to say that many of these lessons are already reflected in our conclusions and recommendations in the Interim Report. [Annex J](#) points to where each lesson is covered in this report and also notes where we have developed new conclusions or recommendations to encompass the Japanese lesson.

DISCUSSION

Introduction

- 711 Our Interim Report on the implications for the UK nuclear industry of the Japanese earthquake and tsunami reached 11 conclusions and identified 26 recommendations. As reported earlier in this report, industry, regulators and Government all responded constructively to those recommendations and have initiated significant programmes of work to see what lessons there are and, if appropriate, to implement improvements to both plant and procedures at and around UK nuclear licensed sites. These responses epitomise the application of the fundamental principle for sustained high standards of nuclear safety – that of continuous improvement – which must remain a cornerstone of the UK nuclear industry’s safety culture, as highlighted in our Interim Report.
- 712 In this Discussion section we consider information that has been made available since our Interim Report, along with input from submissions to us and responses from the industry and others. In keeping with our culture of continuous improvement, we also review and build upon our earlier conclusions and recommendations, and go on to make further proposals. This striving for improvement does not mean that existing plants are unsafe or that we must curtail their operation. However we are clear that if, in the light of information on the Fukushima accident, we were to become dissatisfied with the on-going safety of any existing UK nuclear facilities we would not hesitate to take appropriate action.
- 713 A number of authoritative reports have been published over the summer. These include a substantial report from the Japanese government to the IAEA Ministerial Conference; the report of an IAEA fact-finding mission to Japan; and the report of the US NRC Near-term Task Force review of insights from the Fukushima accident. We recognise the importance of learning from others and have reviewed each of these documents. They have proved very helpful in clarifying our understanding of the accident progression and have provided insights into safety and emergency preparedness issues in a number of areas, as outlined below. Our Interim Report covered nearly all of the recommendations of these reports – see [Annex I](#) and [Annex J](#).
- 714 We note that although the Japanese authorities have released much further information as their investigations and analyses have progressed, their continuing priority is to establish secure and sustainable control over cooling and containment of radioactivity at the site so as to protect workers, public and environment, and to allow off-site recovery actions. The operator, TEPCO, has outlined the actions it plans to undertake to achieve this in its *“Roadmap towards restoration from the accident at Fukushima Daiichi nuclear power station”*. Latest information indicates that progress continues to be made.
- 715 There are, of course, still some uncertainties in our detailed knowledge of events, and it may be some time before certain details are validated. Such uncertainties are not surprising given the nature of severe nuclear accidents. Although few in number, these have invariably been characterised by a loss of control of operations and a degradation of information about plant status. The severe accidents at Windscale, Three Mile Island, Chernobyl, and now Fukushima-1, have shown that instrumentation may not be qualified for the extreme environmental conditions (temperature, pressure, water immersion etc.) that can arise in such accidents. At Fukushima-1 the electrical supplies needed to gather information from this instrumentation were also not available for extended periods.
- 716 Uncertainties about the technical details of the accident do not, however, prevent us from drawing conclusions about its causes and about the subsequent emergency response both on-site and in

the surrounding area. Above all, we should to seek to draw early lessons wherever we can and to ensure those lessons are put into action in the UK as soon as possible. Although sufficient was known by the time the Interim Report was finalised to enable us to draw out key conclusions and recommendations, the additional information that has become available in the intervening period has enabled us to review, validate, refine and supplement these as appropriate. We will continue to review and act upon any detailed technical information that emerges from future scientific analysis of the accident or subsequent research.

- 717 In this section, we first draw out salient features from the reports published by the IAEA mission and by the government of Japan. We also summarise the US NRC's Task Force report. We then go on to consider whether additional conclusions and recommendations can be drawn by examining the UK regulatory system, the regulatory regime's goal-setting approach to assuring safety, and the defence-in-depth principle. In doing so, we consider whether the accident has implications for the effectiveness of the safety analysis methodology used in the UK, and examine existing guidance to ONR's Inspectors in our SAPs and how these relate to issues that are manifest in the Fukushima accident. We also note the links between this work and the "Stress Tests" initiated by the Council of the European Union.
- 718 Finally, using this new information and input, together with developments in our thinking and understanding, we review the Interim Report conclusions and recommendations.

Reports from International Authorities

IAEA Fact-finding Mission

- 719 Following the accident at Fukushima-1, IAEA initiated a number of activities in order to draw lessons from the accident, assist the Japanese authorities and report to IAEA member states. With the agreement of the Japanese government the Agency organised a preliminary mission to find facts and identify initial lessons to be learnt. This mission was undertaken by a team made up of experts from across the world and Agency staff. It was conducted from 24 May to 2 June 2011.
- 720 The mission team received excellent co-operation from all parties, and received information from Japanese ministries, nuclear regulators and operators. The team also visited three affected nuclear power facilities – Tokai, Fukushima-1 and Fukushima-2 – to gain an appreciation of the status of the plant at each site and the scale of the damage. These visits allowed the experts to talk to the operations staff as well as to view plant damage, and to see the work being undertaken to recover control and mitigate the consequences of the accident. The first hand knowledge that they gained and their conclusions and recommendations have helped to inform our own thinking on lessons to be learnt from the accident.
- 721 A crucial initial finding of the mission team was that the tsunami risk for several sites in Japan had been underestimated. It also concluded that nuclear regulatory systems should ensure that there are adequate arrangements for addressing extreme events, including the periodic review of those arrangements. It also highlighted a need for regulatory independence and clarity of roles in all circumstances. These initial findings were confirmed in the final mission report presented to a week-long Ministerial Conference convened by IAEA in Vienna in late June 2011. The mission report contained 15 conclusions and 16 lessons for the global nuclear community. These covered areas such as:
- Consideration of external hazards and the management of severe accidents.
 - Emergency arrangements.

- IAEA Safety Standards including the role of the regulator.

- 722 The Japanese government reported to this conference that the main nuclear regulator (NISA) would be split from METI and combined with other agencies to form an independent regulatory body.
- 723 The IAEA mission report was discussed at a special session of the ministerial meeting and, along with other sessions on emergency response and impact on the global nuclear safety system, formed the basis of the development of an IAEA action plan for consideration by the IAEA Governors in September 2011.
- 724 We have reviewed their conclusions and recommendations against our Interim Report findings (see [Annex I](#)) and found them to be largely covered.

Report of the Japanese Government

- 725 The Japanese government presented a substantial report on the accident to the Ministerial Conference. This provided a comprehensive description of the regulatory framework for nuclear safety; the damage resulting from the earthquake and tsunami; the accident at Fukushima-1; the emergency response; radioactive releases to the environment; radiation doses; international co-operation; communication of information; actions to re-establish full control of the site, and lessons learnt to date. The report included a detailed timeline of events at the six Fukushima -1 reactor units and conclusions on the progression of core damage based upon computer modelling of these events. This information has helped us to understand the progression of the accident and informed our thinking on issues important to accident analysis and severe accident management.
- 726 The report of the Japanese government includes two separate estimates of the amount of radioactivity released into the environment, calculated on different bases. NISA estimates of this “source term” were based upon the Japan Nuclear Energy Safety organisation’s (JNES) calculations of the accident progression from loss of cooling, through core degradation, to fission product release to the environment. Japan’s Nuclear Safety Commission (NSC) estimates were based instead upon IAEA calculations from environmental monitoring measurements, so these were not reliant upon knowledge of the accident progression. These two calculational routes gave similar results of $1-2 \times 10^{17}$ Bq of I-131 and $1-2 \times 10^{16}$ Bq of Cs-137, which are about 10% of the releases of these radioisotopes at Chernobyl. On this basis, the Japanese authorities raised the INES rating to Level 7 from its original declaration of Level 5 which was made before the release estimates were available. These calculations were not undertaken until some time after the start of the accident and did not influence the Japanese authorities’ decisions on off-site countermeasures. This is unsurprising since off-site monitoring arrangements had been severely disrupted in the early days and it took some time to gain confidence in key plant parameters, such as water levels in the RPVs, thus inhibiting early analysis.
- 727 Radioactively contaminated water leaked from the damaged RPVs into the surrounding buildings and basements, and some subsequently leaked into the sea. The Japanese authorities estimate that 4.7×10^{15} Bq of radioactivity was released into the marine environment before the leak path to the sea was sealed. There remains a pathway for further leakage through possibly contaminated ground water, but action is being taken against this hazard.
- 728 The dose limit for emergency workers was raised from 100 to 250mSv. Initially, many electronic dosimeters were inoperable as they had been immersed in water, so the few still functioning were given to team leaders to provide group measurements. By 23 May 2011, 7800 workers had been

deployed and received an average dose of 7.7mSv, 30 had doses >100mSv and some of the latter might exceed doses of 250mSv in the future once internal dose is taken into account. Two workers who stepped into highly contaminated water received doses to their legs / feet of up to 3Sv.

729 It has been reported that three on-site workers died following the earthquake and tsunami and several more were injured, but there have been no fatalities reported from exposure to radiation. Off-site, nearly 20,000^{†††} people have been reported as dead or missing as a result of the earthquake and tsunami. By 31 May 2011 almost 200,000 members of the public had been given health screening for radiation effects and around 1000 children had had thyroid screening, but no significant health consequences were identified.

730 The Japanese government's report contained 28 detailed lessons covering areas such as:

- The need to strengthen preventive measures against earthquakes, tsunamis and severe accidents, and ensure power and cooling supplies.
- To make severe accident management measures legal requirements, and to develop these measures utilising a PSA approach and ensuring effective training for response to severe accidents.
- The need for enhanced communications relevant to accidents, including better international co-ordination and improved capability for predicting off-site effects.
- The need to improve human resource development including nuclear safety education, nuclear emergency preparedness and response, crisis management and radiation medicine (medical diagnosis and treatment).
- Reinforcement of the nuclear safety bodies by ensuring greater independence.
- Instilling safety culture.

731 Again, we have reviewed their detailed recommendations against our Interim Report findings (see [Annex J](#)) and have found them to be largely covered.

Report of the US NRC's Near-term Task Force

732 The US NRC directed its staff on 23 March 2011 to set up a task force to review US nuclear regulatory processes and regulations and advise on whether improvements were needed in the light of the Fukushima accident. The report from this review has now been published and this has also informed our thinking.

733 The US nuclear regulatory system may be characterised as prescriptive and rule-based. The report of the "Near-term Task Force" has a different focus to the IAEA and Japanese government reports, in that it concentrates on exploring implications of the accident for US nuclear safety rules and regulations. It is structured around the functions of ensuring protection against faults, enhancing mitigation and strengthening emergency preparedness. In particular, it provides expert commentary on the concepts of defence-in-depth and the "design basis" of plant. The task force made a total of 12 recommendations; many of those which are not specific to plant design or regulatory system align with our own. They mainly cover:

- Clarification of the regulatory framework to have an appropriate balance between defence-in-depth and risk considerations.

^{†††} Latest estimates compared with the previous 25,000 dead or missing.

- Ensuring Protection – re-evaluate and upgrade as necessary design basis seismic and flooding protection.
- Enhancing mitigation – for instance strengthening station blackout mitigation.
- Strengthening emergency preparedness for prolonged station blackout and multi-unit events.
- Improving the efficiency of NRC regulatory oversight of licensee safety performance.

Stakeholder Submissions and Industry Responses

- 734 To help inform our Interim and Final Reports we invited stakeholders, via the ONR website, to submit any information they considered might be relevant. In total, 73 submissions were received for our Interim Report and 53 for this Final Report within the timescales set to enable detailed consideration, and we are grateful to all who contributed in this way. Submissions were received from a wide range of stakeholders, including non-governmental organisations, nuclear industry representatives, government, international nuclear organisations, academics and members of the public. Some respondents were clearly in favour of nuclear power, whilst others were clearly against. The range of comments was broad covering for example, seismic activity, tsunamis, emergency planning arrangements and the scope of our reports. All submissions were reviewed by nuclear safety inspectors for relevant information on potential lessons for the UK nuclear industry and for us as regulators.
- 735 In particular, the submissions were scrutinised for information on the causes or the progression of the accident, insights into the behaviour of the plant or personnel, the management of the emergency and suggestions for lessons to be learnt. When new information was identified, it was forwarded to nuclear safety inspectors with relevant technical expertise to be considered during the drafting of specific sections of the Interim and Final reports. Some points raised covered matters which were outside the focus of the report or beyond our role and responsibilities, for example covering national policy issues, and these were not reviewed. Some others referred to comments on other reports such as the IAEA report and these were considered alongside our review of such documentation.
- 736 As noted above, our work has greatly benefited from many submissions from a wide variety of sources. We have reviewed these along with the responses to the Interim Report recommendations, and the further analysis that we have undertaken, in order to determine whether there are areas where further conclusions or recommendations are warranted. Below we examine the nuclear safety philosophy used in the UK and then look at three key components of ensuring defence-in-depth – accident prevention, mitigation, and protection of the public and workers in the event of a significant nuclear accident.

Consideration of Lessons for the UK Nuclear Safety System and Regulatory Regime

Safety Philosophy

- 737 The UK system for the regulation of health and safety has a goal-setting approach in which safety objectives and outcomes are set out through legislation, but “duty holders” – the operators of the plant – are responsible for identifying the specific technical measures and procedures necessary to meet these objectives. The fundamental objective and legal requirement is to reduce the risks to workers and the public “so far as is reasonably practicable” (SFAIRP), which for assessment purposes is termed “as low as is reasonably practicable” (ALARP). This goal-setting approach is

common to both nuclear safety regulation and other areas of UK safety regulation. It has a number of advantages, for example:

- It places the responsibility for thinking about and controlling the hazards associated with an industrial process with the operators and designers, who have day-to-day control over the operation and detailed knowledge of the plant and processes.
- It is “technology neutral”, in that the detailed way in which the safety objectives are to be achieved is not prescribed by the Regulator, although the Regulator might provide examples of relevant good practice for the operator to consider.
- As details of the technology are not prescribed, the regulations and other legal requirements do not become out-of-date as understanding and technology advances.
- The requirement for duty holders to reduce risks SFAIRP applies at all times, so if advances in understanding and technology allow a process to be conducted in a safer manner, duty holders are obliged to consider modifying their plant to take advantage of this.

738 The nuclear regulatory regime in the UK remains a largely goal-setting one, whereas in some other sectors the UK has responded to pressures, such as detailed European Council Directives, by augmenting the general goal-setting approach with detailed regulations. Although some aspects of nuclear safety are covered by regulations, these (such as IRR99 and REPPiR) have wider industrial application and embody the concept of reasonable practicability. The UK’s nuclear licensing approach is a strongly goal-setting one; a licence is only granted when the Regulator is satisfied with the operating company’s capability to perform effectively as a nuclear licensee and to comply with the standard 36 Licence Conditions that apply to each nuclear site licence.

739 We are aware of some views that our technology-neutral, goal-setting approach provides an insufficiently strong regulatory regime, citing such instances of our use of “recommendations” rather than telling the operators what to do, and of not always prosecuting for non-compliances but seeking earlier more committed improvements by other means. While noting these views, we maintain that the goal-setting approach is fundamental to ensuring that operators own the solutions to problems associated with their operations, and have the desire and capability to understand the hazards arising, as well as how to control them. We believe that this encourages higher levels of sustained nuclear safety, noting that a strong safety culture is one in which staff do what is right for safety when neither the Regulator, or management, are present or likely to see the outcome of their actions.

740 We recognise that another perceived disadvantage of a technology-neutral, goal-setting, non-prescriptive approach is that it tends to place greater reliance on the judgement of individual ONR Inspectors in making recommendations on enforcement and permissioning, leading to a risk of inconsistency. ONR recognises this risk and guards against it by applying rigorous standards in staff recruitment, through continuing learning and development processes and by means of management controls on regulatory decision-making, as well as through guidance to its safety inspectors in the form of SAPs and supplementary TAGs, all of which are published.

741 The nuclear safety regulator’s role is to ensure that duty holders are properly fulfilling their responsibilities, which it does by inspecting activities, scrutinising their standards of design and operation, assessing their safety cases, taking enforcement action when shortcomings are found, and challenging duty holders to do more to reduce risks.

742 The Japanese regulatory system has features that are fundamentally different to those in the UK, including a much more prescriptive approach, a different approach to design basis and periodic

review of safety for older plant, and the regulator being part of a central government department. Having considered these differences and other matters, our view remains that the basic philosophy of nuclear safety regulation and the system of regulation in the UK is robust and the further information we have received about the facts surrounding the Fukushima accident reinforces this view. This view is endorsed by the conclusions of independent peer reviews of the UK regulatory system at the review meetings of the various international conventions as well as the two IAEA review missions. We therefore consider Conclusion IR-5 of our Interim Report remains valid:

Conclusion IR-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.**

Safety Assessment Principles

- 743 Some have commented on the use of PSA by regulatory authorities and industry, seemingly considering that the use is the same across the world including Japan, USA, France and the UK. They have concluded that therefore, in the context of Fukushima, there are implications for the UK system. The use is not the same and essential differences are apparent in the context of Fukushima as is discussed below.
- 744 ONR's SAPs for nuclear facilities were first published in 1979 and revised and republished several times, most recently in 2006. The SAPs provide guidance to ONR Inspectors to help them to make informed and consistent judgements on the adequacy of safety cases submitted by nuclear licensees to support requests to implement safety significant proposals. These proposals may range from a minor plant modification, for example, changes to an existing pump, to major construction, for example a new nuclear power station. The level and scope of documentation required to support a proposal increases in proportion to the project scope and its safety significance.
- 745 Over the years the scope of the SAPs has been expanded, first to cover both nuclear reactors and nuclear fuel cycle facilities, then to incorporate developments in PSA methodology, and most recently to include "softer" issues such as leadership and management for safety, safety management systems and emergency arrangements, and also to make explicit their application to existing plant. The most recent revision of the SAPs was benchmarked against the IAEA Safety Standards to ensure that international good practice embodied in these standards and associated guides was taken into account.
- 746 The SAPs are not prescriptive and a duty holder does not have to satisfy ONR that every single SAP has been met by a safety case since, given the diverse range of operations conducted at nuclear installations in the UK, some will not apply. They do, however, set out the issues that a safety case would potentially need to address in order to demonstrate to ONR's satisfaction that the safety of a proposal would be assured, and so gain regulatory permission.
- 747 Every accident inevitably raises the question of whether the prevailing design standards were inadequate, or whether they were sound but inadequately implemented. A critical question raised by the Fukushima accident is whether it has shown that existing nuclear safety standards and

^{***} In this section we have identified the Interim Report conclusions and recommendations with the prefix "IR" and those that are new in this Final Report by the prefix "FR" to provide clarity.

guidance have significant shortcomings or gaps and, if so, how widespread these are. Such a finding could have major implications for confidence in the methodologies for nuclear safety analysis, as it would suggest that analysts were unable to predict important fault initiators and design adequate protection against them. The adequacy of our SAPs in the light of issues raised by the Fukushima accident is consequently considered below.

- 748 There is an accepted hierarchy of measures for preventing harm. Under this hierarchy, designers and operators of plant seek to:
- Prevent faults that could escalate into accidents with significant consequences from developing – usually by incorporating protection systems capable of arresting fault progression before plant or systems move outside their design limits.
 - Mitigate the consequences of faults for which the protection proves ineffective.
 - Protect the public, workers and environment from harm in the event that accident mitigation proves ineffective.
- 749 We follow this hierarchy below in considering the key question about design basis assessment methodology and lessons from the Fukushima accident, drawing on the further information available, our additional analysis and the submissions we have received.

Accident Prevention

Overview of the Fukushima Accident

- 750 The accident resulted from the Fukushima-1 site being hit by two related natural events in less than an hour, the combined impact of which rendered several safety systems ineffective. Initially there was the earthquake of magnitude 9.0 off the east coast of Japan, now known as the Tohoku event, which led to severe ground motions on and off the Fukushima-1 site. As reported earlier, the operating reactors successfully “scrammed” (rapidly shutdown the nuclear reactions) in response, but connections to, and parts of, the electricity grid failed and the reactors lost all off-site AC power. However, 12 of the 13 large, on-site emergency diesel generators operated (one was out of operation for maintenance) and initially provided sufficient on-site AC power to maintain adequate cooling of the nuclear reactor cores.
- 751 Some have commented on reports of plant damage caused by the earthquake, concluding that the loss of effective cooling for the reactors stemmed directly from the earthquake rather than the subsequent tsunami. However, the information available on the emergency cooling systems and analysis of the circumstances does not support such a hypothesis. The information points to effective cooling at all three operating reactors after the earthquake struck, with cooling being eventually lost for each of these three reactors after the tsunami hit. Reactor Units 5 and 6 on the Fukushima-1 site did not lose effective cooling and were shown to be robust despite experiencing similar ground motions to Reactors Units 1 to 4. Similarly, reactors on other sites managed to maintain cooling given the continuing availability of electricity supplies and less disruption from inundation from the tsunami. Consequently, it is concluded that damage reported as being observed between the occurrence of the earthquake and the tsunami is likely to have been to non-safety-critical equipment or pipework, especially as the crucial equipment is housed in normally non-accessible areas (and thus not visible to observers). However, we will continue to monitor information in this area as it may provide further insights into the application of seismic design codes or the performance of non-seismically qualified plant.

- 752 Less than an hour after the initial earthquake the site was hit by large tsunami waves of more than 6m in height, resulting in the inundation of reactor buildings. The site had originally been designed to withstand heights of only OP +3.1m. This remains the regulatory basis, although a study in 2002 had indicated a height of OP +5.7m would be more appropriate and some modifications had been made to Reactor Unit 6 in response. The site was consequently inundated and immersed in water. This, together with damage from entrained debris resulted in the complete loss of AC power to all the reactor units except Reactor Unit 6. In addition, the sea-water pumps that provided cooling to essential plant systems were submerged and stopped operating resulting in a condition known as “loss of ultimate heat sink”. Some batteries providing DC power for instrumentation and actuation of valves etc. were also immersed and became inoperable.
- 753 The result was that operators eventually lost control of core cooling of the three reactors that had been operating when the earthquake struck and, although there were great efforts to restore this, these were ultimately unsuccessful. It is believed that the water coolant covering the reactor cores boiled-off and the fuel, when no longer immersed in water, overheated and its zirconium alloy cladding reacted with the steam to generate hydrogen. The zirconium / steam reaction itself generates heat and this will have accelerated the rate of reaction. Japanese computer modelling, based on assumptions about water levels in Reactor Units 1–3 cores, indicates that the fuel in each would have degraded and at least partially melted and slumped towards the bottom of the RPVs. The hydrogen leaked into the surrounding reactor buildings, and is considered to have been responsible for the subsequent explosions (although some uncertainties remain about the basis for the explosion in the building of Reactor Unit 4).

Implications for Design Basis Analysis

- 754 There have been reports of several large tsunamis of similar, or greater, wave heights hitting the east coast of Japan over its recorded history. This raises the question of why the Fukushima-1 site was not designed to withstand tsunami waves of the heights indicated in historical records. The answer provided by the report of the Japanese government is that:

“compared with the design against earthquake, the design against tsunamis has been performed based on tsunami folklore and indelible traces of tsunamis, not on adequate consideration of the recurrence of large-scale earthquakes in relation to a safety goal ...”.

The basic cause of the accident was thus that the site was not designed with adequate protection against some foreseeable natural hazards. This is a prime conclusion of the IAEA mission report.

- 755 This points to significant shortcomings in the safety analysis methodology used, and that the “design basis” of the reactors was deficient with regard to tsunamis. It is important to understand whether this was a peculiarity of the Japanese approach to nuclear design and safety or a symptom of a wider shortcoming in international nuclear standards and guides.
- 756 The ONR has adopted the IAEA definition of “design basis” in its SAPs, namely:

“the range of conditions and events that should be explicitly taken into account in the design of the facility, according to established criteria, such that the facility can withstand them without exceeding authorised limits by the planned operation of safety systems”.

This range of conditions and events is identified in different ways in different national regulatory systems.

757 The Japanese approach is set out in the Japanese NSC Regulatory Guide for Reviewing Safety Assessment of Light Water Nuclear Power Reactor Facilities (Ref. [32](#)). In that document, the NSC sets out the “anticipated operational occurrences” and “accidents” that must be analysed to satisfy the regulator of the safety of a light water reactor before it may be installed or modified. Only a single failure of a safety system or component within it needs to be assumed following the initiating event. Appendix I of the Guide describes the typical events that should be postulated for analysis together with respective analytical conditions.

758 This is an example of a prescriptive and deterministic approach to safety regulation. It is prescriptive because the regulator prescribes the faults that must be analysed in order to demonstrate safety and gain regulatory permissions. It is deterministic because the analyses are intended to demonstrate on a conservative basis that the built-in protection would be effective in terminating the faults considered without significant consequences, without explicitly considering the likelihood of these or other possible fault sequences.

759 The report of the Japanese government stated that neither total loss of AC power nor loss of ultimate heat sink were design basis events. However, a trial tsunami PSA carried out stated:

“...indicated that the risk sensitivity of an event in which simultaneous functional losses of all the seawater pumps are generated due to tsunami was high”.

760 Nuclear facility designs need to incorporate adequate protection against all events that could initiate an accident with significant consequences. The goal-setting approach taken in the UK combines a probabilistic identification of the faults to be considered, along with a deterministic analysis of representative faults, to demonstrate that the protection would be effective. ONR’s fault analysis SAPs state that:

Principle FA.1: *Fault analysis should be carried out comprising design basis analysis, suitable and sufficient PSA, and suitable and sufficient severe accident analysis.*

Principle FA.2: *Fault analysis should identify all initiating faults having the potential to lead to any person receiving a significant dose of radiation, or to a significant quantity of radioactive material escaping from its designated place of residence or confinement.*

Principle FA.3: *Fault sequences should be developed from the initiating faults and their potential consequences analysed.*

Principle FA.4: *DBA should be carried out to provide a robust demonstration of the fault tolerance of the engineering design and the effectiveness of the safety measures.*

Principle FA.5: *The safety case should list all initiating faults that are included within the design basis analysis of the facility.*

Principle FA.6: *For each initiating fault in the design basis, the relevant design basis fault sequences should be identified.*

761 SAP FA.2 requires the identification of all events that could initiate a fault with the potential to lead to significant consequences. The text following SAP FA.5 states that the list of those to be considered within the design basis may exclude plant faults with initiating frequencies less than about 1 in 100,000 years and natural hazards with predicted frequencies of less than 1 in 10,000

years. It also notes that design basis fault sequences should include as appropriate “failures consequential upon the initiating fault, and failures expected to occur in combination with that initiating fault arising from a common cause” as well as single failures of safety measures.

762 The engineering SAPs for internal and external hazards elaborate upon these as follows:

Principle EHA.3: *For each internal or external hazard, which cannot be excluded on the basis of either low frequency or insignificant consequence, a design basis event should be derived.*

Principle EHA.4: *The design basis event for an internal and external hazard should conservatively have a predicted frequency of exceedence of no more than once in 10,000 years.*

Principle EHA.6: *Analyses should take into account simultaneous effects, common cause failure, defence in depth and consequential effects.*

Principle EHA.12: *Nuclear facilities should withstand flooding conditions that meet the design basis event criteria.*

763 The supporting text states that “the area around the site should be evaluated to determine the potential for flooding due to external hazards e.g. precipitation, high tides, storm surges, barometric effects, overflowing of rivers and upstream structures, coastal erosion, seiches and tsunamis”, and “the design basis flood should take account, as appropriate, of the combined effects of high tide, wind effects, wave actions, duration of the flood and flow conditions”.

764 It is clear that, in developing the SAPs, ONR inspectors anticipated potential combinations of events such as occurred at Fukushima-1 and the UK consequently has a robust, structured and comprehensive methodology for identifying design basis events. This reinforces Conclusion IR-4 of our Interim Report and we further conclude:

Conclusion FR-1: Consideration of the accident at Fukushima-1 against the ONR Safety Assessment Principles for design basis fault analysis and internal and external hazards has shown that the UK approach to identifying the design basis for nuclear facilities is sound for such initiating events.

765 Some have queried whether application of such principles would increase costs for construction of new power stations on sites identified as potentially suitable located in Flood Zone 3 areas, particularly in the light of Conclusion IR-6 of our Interim Report which said:

Conclusion IR-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.

766 To put in additional flood protection, or revise layouts for nuclear power station sites in Flood Zone 3, would be certain to increase costs. In coming to Interim Report Conclusion IR-6 we were clearly

^{§§§} The prefix “IR” has been to identify clearly those conclusions from the Interim Report. Conclusion IR-1 here is therefore the same as Conclusion 1 in the Interim Report.

not commenting on the economics of a nuclear power station development but on the likely availability of design solutions, albeit at a cost, and on the ability of our regulatory system, particularly through SAPs, to ensure the adequacy of safety against flooding at such sites, should construction proposals come forward.

Responding to Advances in Technology and Standards

- 767 The six reactors at Fukushima-1 entered service between 1971 and 1979, with the designs originating in the 1960s. The oldest nuclear power station in the UK that is still operating is Oldbury, which entered service in 1967. The modern standards noted above post-date the construction and commissioning of these sites. This raises the question of how regulators ensure that the safety standards achieved at older facilities do not fall far behind those at more modern plant, leaving potential vulnerabilities unresolved, noting that the regulatory design basis requirement for tsunamis at Fukushima-1 had remained throughout the plants' lifetime at its original level of OP +3.1m.
- 768 ONR and its predecessors have, for some decades, required nuclear site licensees to undertake 10-yearly PSRs. This aligns with IAEA safety standards and guides and in the UK is a legal requirement enforced through nuclear site licence Licence Condition 15. The licensee has to agree the scope of the PSR with ONR before it starts the review and submit reports of the PSR to ONR following its completion. As well as reporting on the review, these reports identify any improvements such as plant modifications that the licensee has decided to implement to close any gaps between the existing standards and modern standards at the facility.
- 769 ONR assesses the PSR reports, using the SAPs as guidance, and considers whether the licensee has provided an adequate demonstration that it can properly manage nuclear safety throughout the following 10 year period. If satisfied on this point, ONR permits continued operation past the 10 year "decision date", subject to the licensee continuing to satisfy it on safety throughout the following period. ONR has often required the licensee to implement improvements, in addition to those it has itself identified, in order to permit continued operation.
- 770 A PSR comprises three elements****. First, it needs to demonstrate that the facility still meets its original design standards and that age-related degradation or past plant modifications have not undermined this. Next, the PSR must consider any issues that might limit the future life of the facility or its components and explain how they will be managed. Finally, it must review the safety case against modern standards and identify any emerging gaps. Modifying existing plant to meet modern standards is more difficult than revising the design of a plant proposed for future construction, so it is not always possible to close the gap completely. Nonetheless, the legal duty to reduce risks "so far as is reasonably practicable" (SFAIRP) means that licensees must consider all the options for closing the gap and implement any reasonably practicable improvements. In the case of Trawsfynydd, one of the older Magnox stations with steel pressure vessels which all ceased operations some years ago, the licensee considered the economic costs of maintaining adequate safety margins would be so great that it decided not to make changes and the reactors were shutdown permanently.
- 771 Substantial plant modifications have been made as a result of the PSRs. These included enhancing the reliability of the Magnox reactor shutdown systems, reinforcing their cooling under shutdown

**** See "Report by HM Nuclear Installations Inspectorate on the Results of Magnox Long Term Safety Reviews (LTSRs) and Periodic Safety Reviews (PSRs)", Ref. [69](#).

conditions through installation of additional cooling capability, and improving their resistance to seismic events. ONR's predecessor published a report^{††††} which estimated the cost of these improvements to be about £100 million. The more modern AGR stations have also been subject to the same review process and have implemented major modifications as a result.

772 UK nuclear site licensees are therefore required to perform regular reviews of the safety cases of their facilities and, if gaps are found, compared with modern standards are legally bound to implement any reasonably practicable improvements to close those gaps. If ONR considered that the improvements proposed by the licensee were insufficient to enable the facility to be operated adequately close to modern standards, it would not permit operations to continue.

773 The requirement to perform PSRs applies equally to nuclear fuel cycle and decommissioning facilities. In some facilities that are no longer operational, but in which nuclear materials are stored prior to their complete decommissioning, it is neither reasonably practicable nor possible in some cases to close the gap with modern standards sufficiently, or possible to call an immediate halt to storage. The Sellafield legacy fuel storage ponds and intermediate level waste storage silos are the prime examples of such facilities. The physical structures and conditions within these decades-old facilities have degraded over the years and they now present risks which are of significant regulatory concern.

774 ONR has taken action on two fronts in response. First, it has used its legal powers to require the licensee to progressively reduce the hazard by undertaking waste retrievals and to decommission the facilities as soon as reasonably practicable. Second, it has engaged with other authorities and Government departments with responsibilities for Sellafield to appraise them of the risks and of the need for adequate financing in order to expedite risk reduction and decommissioning. As a result the licensee, the Nuclear Decommissioning Authority (NDA, which owns the site) and Government, all regard urgent progress with the legacy ponds and silos remediation and retrievals programme as a national priority. This priority is reinforced by the example of the Fukushima accident where the vulnerabilities of older plant were not sufficiently recognised and addressed.

Conclusion FR-2: The Fukushima accident reinforces the need for the Government, the Nuclear Decommissioning Authority and the Sellafield Licensee to continue to pursue the Legacy Ponds and Silos remediation and retrievals programme with utmost vigour and determination.

775 By way of contrast, the report of the Japanese government states that PSRs were carried out by Japanese licensees on a voluntary basis and, although some aspects of these were made mandatory in 2003, the provision of a PSA to assess the overall risks presented by the sites remained voluntary and the regulator ceased performing reviews.

Conclusion FR-3: The mandatory requirement for UK nuclear site licensees to perform periodic reviews of their safety cases and submit them to ONR to permit continued operation provides a robust means of ensuring that operational facilities are adequately improved in line with advances in technology and standards, or otherwise shut down or decommissioned.

^{††††} Magnox nuclear power reactor programme: Nil's report on the outcome of the programme of generic safety issues, Ref. [70](#).

- 776 The quality and timing of PSR submissions from non-nuclear power plant site licensees has nevertheless fallen short of regulatory requirements on some occasions in the past, and ONR has had to serve Improvement Notices under HSWA74 on licensees to secure compliance. The Fukushima accident has reinforced the need for all licensees to give sustained priority to completing PSRs and implementing identified reasonably practicable improvements.

Recommendation FR-1: All nuclear site licensees should give appropriate and consistent priority to completing Periodic Safety Reviews (PSR) to the required standards and timescales, and to implementing identified reasonably practicable plant improvements.

- 777 We will be engaging with licensees at a senior management level to reinforce this lesson.

Accident Mitigation

- 778 The UK legal requirement to reduce risks SFAIRP is not confined to the design basis. One of the Fundamental Principles in ONR's SAPs states:

Principle FP.7: *All reasonably practicable steps must be taken to prevent and mitigate nuclear or radiation accidents.*

- 779 This is reinforced by an accident management SAP:

Principle AM.1: *A nuclear facility should be so designed and operated to ensure that it meets the needs of accident management and emergency preparedness.*

- 780 The text following this SAP notes that:

“accident management strategies should be developed to reduce the risk of accidents. Fault analysis should be used to form a suitable basis for the development of these strategies. The strategies should primarily aim to prevent the breach of barriers to release or, where this cannot be achieved, to mitigate the consequences. The ultimate objective should be to return to a controlled state in which a plant can be maintained in a safe stable condition. The strategies should identify any instrumentation needed to monitor the state of the plant and the level of severity of the accident, and any equipment to be used to control the accident or mitigate its consequences. Where additional hardware would facilitate accident management, this should be provided if reasonably practicable. It may also be of a different type, robustness and in a different location to that provided for normal operations”.

- 781 As already noted, the report of the IAEA fact-finding mission to Japan found that the on-site emergency response at Fukushima-1 benefited from the site having a modern emergency response centre which had been hardened against external hazards. This provided a protected area from which station staff could manage emergency actions when the reactor control rooms became untenable. However, the report also noted that some emergency actions were frustrated by adverse environmental conditions, such as high radiation dose rates and electronic dosimeters failing due to having been immersed in water.

- 782 Combining these lessons with the preceding SAPs leads to the recommendations:

Recommendation FR-2: The UK nuclear industry should ensure that structures, systems and components needed for managing and controlling actions in response to an accident, including plant control rooms, on-site emergency control centres and off-site emergency centres, are adequately protected against hazards that could affect several simultaneously.

Recommendation FR-3: Structures, systems and components needed for managing and controlling actions in response to an accident, including plant control rooms, on-site emergency control centres and off-site emergency centres, should be capable of operating adequately in the conditions, and for the duration, for which they could be needed, including possible severe accident conditions.

783 These recommendations, together with those for licensees below, apply to all UK nuclear site licensees whether operating power reactors or other nuclear facilities. They reinforce and supplement Interim Report Recommendations IR-22 and IR-23, which state:

Interim Report Recommendation IR-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.

Interim Report Recommendation IR-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.

784 In order to appreciate the environmental conditions that could arise in severe accidents and identify any reasonably practicable measures that might be taken to mitigate their consequences, it is necessary to understand the physical and chemical phenomena that could occur, the circumstances under which they might occur, and their likelihoods. This is set out in two of the Fault Analysis SAPs:

Principle FA.15: *Fault sequences beyond the design basis that have the potential to lead to a severe accident should be analysed;*

Principle FA.16: *The severe accident analysis should be used in the consideration of further risk-reducing measures;*

and the supporting text which states:

“severe accident analysis should provide information:

- a) to assist in the identification of any further reasonably practicable preventative or mitigating measures beyond those derived from the design basis;*
- b) to form a suitable basis for accident management strategies;*
- c) to support the preparation of emergency plans for the protection of people; and*
- d) to support the Probabilistic Safety Analysis (PSA) of the facility’s design and operation.”*

- 785 PSAs may be performed to three different levels, depending on the type of risk information sought. Level 1 PSAs provide information on the nature and probabilities of fault sequences and of accidents beyond the design basis, but give no information on the magnitudes of releases of radioactivity to the environment and their frequencies. Level 2 PSAs combine analyses of the probabilities of different potential accident sequences with an understanding of severe accident progression and the barriers to fission product release in order to provide information on the frequencies and characteristics of different fission product releases to the environment. Level 2 PSAs also act as bases for severe accident management measures and associated operator actions. Level 3 PSAs go a step further, and combine this information with models of the dispersion of radioactive materials in the environment to provide information on the risks to public health and other societal and environmental detriments.
- 786 The information needed by SAPs FA.15 and FA.16 requires a PSA to at least Level 2. This would enable analysts to understand the risk profiles of different plants and identify any vulnerabilities that might be reduced by implementing improvements. A Level 3 PSA would provide additional information, but this could not be used by the licensee to enhance on-site accident mitigation measures. We consequently have an additional conclusion and recommendation:

Conclusion FR-4: The circumstances of the Fukushima accident have heightened the importance of Level 2 Probabilistic Safety Analysis for all nuclear facilities that could have accidents with significant off-site consequences.

Recommendation FR-4: The nuclear industry should ensure that adequate Level 2 Probabilistic Safety Analyses (PSA) are provided for all nuclear facilities that could have accidents with significant off-site consequences and use the results to inform further consideration of severe accident management measures. The PSAs should consider a full range of external events including "beyond design basis" events and extended mission times.

Public Protection

Countermeasures to Protect the Public

- 787 Less than 24 hours after the earthquake, the Japanese authorities initiated evacuation of the public from within 3km of the Fukushima-1 site. They extended the evacuation radius to 20km less than 24 hours later. Four days after the earthquake the area in which members of the public were advised to shelter in their homes was extended from 3–10km to 20–30km. These measures appear to have been effective in helping to protect the public given the results of the subsequent monitoring programme. This is despite the absence of early information and diagnosis (due to crucial instrumentation and monitoring capability on and off the site being lost after the earthquake and tsunami) and some delay in the issue of potassium iodate tablets.
- 788 Each UK nuclear licensed site with the potential for accidents with off-site radiation consequences is required to establish a DEPZ, for which the local authority must make detailed plans to protect people in a radiation emergency. The radii of these zones have been set by considering releases of radioactive materials from accidents which can be reasonably foreseen, taking account of the most significant design basis accidents derived from the site safety cases. These zones may also be influenced by local factors, e.g. the presence of a neighbouring nuclear site, and have been subject

to the agreement of ONR or its predecessors. Detailed actions have not been identified for beyond design basis accidents, either within or beyond the DEPZ, because it has been considered impracticable to make detailed plans against very uncertain and improbable events. Instead, existing plans are capable of being extended to deal with a larger than “reasonably foreseeable” accident, based on civil emergency contingency arrangements.

- 789 The radii of the DEPZs around UK nuclear power stations range from 1km for Heysham and Hartlepool to 3.5km for Hinkley Point, which is common to both the Magnox and AGR stations at that location. The minimum DEPZ radius that is permitted for a licensed site for which a radiation emergency is reasonably foreseeable in the UK is 1km. A minimum radius is set to provide a basis for extending countermeasures for the protection of the public to wider areas in the event of an accident with greater off-site consequences than the reasonably foreseeable accident for the site.
- 790 The licensees also maintain arrangements for monitoring radioactivity in the environment to distances of 15km for the AGR stations and Sizewell B, and 40km for the Magnox stations. This is to inform any decisions in an emergency on the need for restrictions on the consumption of milk and other foodstuffs.
- 791 Other countries have different approaches, some based on extendibility and others having more detailed plans going out further, including for re-location where there are high external dose rates. The lessons from Fukushima in this area show the need for effective pre-planned detailed emergency zones but which are easily extended in a controlled way.
- 792 In our Interim Report we recommended a review of the UK’s emergency arrangements through Recommendation IR-3 which stated:

Recommendation IR-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.

- 793 The radii established for emergency planning zones must, of course, depend on the radiological releases that are considered reasonably foreseeable and the practicability of implementation of the emergency plans. However, as it is considered that licensees should review on-site measures to improve resilience to severe accidents in the light of the Fukushima accident, it follows that the practicability and effectiveness of the arrangements for extending countermeasures beyond a small DEPZ in the event of more serious accidents should also be reviewed. It is therefore considered that NEPLG should examine the need to enhance the UK’s extendibility arrangements for extending countermeasures beyond the DEPZ in the event of more serious accidents.
- 794 The practicability of implementing off-site countermeasures is inextricably linked to the density and distribution of people around the nuclear site. A site that was acceptable for emergency planning purposes when it was first established may not continue to be acceptable unless planning controls limit population growth in the site’s locality, or action can be taken to ensure the off-site emergency countermeasures can cope with the changed demographic. In making decisions on planning consent for developments near to nuclear sites, it is therefore vital that ONR’s expert advice on these matters continues to be given full consideration by the relevant planning authorities. In light of the events at Fukushima, we consider that it is timely for the relevant Government departments in the UK to examine the existing system of planning controls for developments in the vicinity of nuclear sites and consider the need for improvements.

Recommendation FR-5: The relevant Government departments in England, Wales and Scotland should examine the adequacy of the existing system of planning controls for commercial and residential developments off the nuclear licensed site.

Data Needed to Support Countermeasure Decisions

- 795 Two broad activities are needed in order to take decisions on the countermeasures needed to protect the public off-site in the event of an accident. Firstly, there must be prognosis: information on the course of the on-site accident is needed to develop an understanding of potential future threats to the surrounding population. This may enable decisions on off-site countermeasures to be taken before members of the public are adversely affected and may enable people to move out of harm's way before any significant release of radioactivity occurs. Secondly, there must be diagnosis: information on the characteristics of radioactivity released from the facility needs to be combined with weather, and possibly marine or watercourse flows, in order to assess its transport through the environment and potential health and environmental effects.
- 796 Prognosis on the course of the accident at Fukushima-1 was very difficult because, as already noted, the loss of electrical power to reactor instrumentation and the devastation on the site severely limited the flow of data on conditions in the six reactor units. Following the Three Mile Island accident in 1979, US research and studies into severe LWR accidents showed that the outcomes of a potential severe accident initiating event can range from the benign to major core damage depending on the timing and effectiveness of actions such as emergency injection of water. The lack of comprehensive data at Fukushima-1 made early effective prognosis virtually impossible.
- 797 For many observers following the news media, the risk to the public and the possibility of major releases of radioactivity to the environment only became apparent with the Reactor Unit 1 explosion the day after the earthquake. Prior to this, only those people less than 3km from the site had been advised to evacuate to more distant locations. Within three hours of this explosion, the Japanese authorities extended the area for evacuation from 3 to 20km.
- 798 In the absence of effective prognosis, diagnosis becomes even more important. It has been reported that although the Japanese SPEEDI (System for Prediction of Environment Emergency Dose Information) was available to predict radiation dose contours in the surrounding countryside, there was no reliable input data on the radioactive source terms. This was due to the state of some radiological monitoring instrumentation on and off the site after the earthquake and tsunami. Such information is crucial to allow quantitative predictions of radioactive material and potential doses to members of the public.
- 799 Prediction of off-site consequences consequently needs real-time data on radioactive releases and weather information. Major UK nuclear sites are equipped with emergency perimeter gamma monitoring systems for detecting any radioactivity passing over the site perimeters, and with weather stations providing local meteorological information, e.g. wind speed and direction. Radiation monitoring vehicles provide off-site information on air concentrations and ground deposition of radioactive materials in the area around the site. However, experience from UK emergency exercises, when coupled with our greater understanding of the Fukushima accident, and from other experience such as the dispersal of material from Eyjafjallajokull volcano in Iceland, suggests that countermeasures advice would benefit from further development of source term measurement techniques and dispersion and consequence modelling.

Recommendation FR-6: The nuclear industry with others should review available techniques for estimating radioactive source terms and undertake research to test the practicability of providing real-time information on the basic characteristics of radioactive releases to the environment to the responsible off-site authorities, taking account of the range of conditions that may exist on and off the site.

Recommendation FR-7: The Government should review the adequacy of arrangements for environmental dose measurements and for predicting dispersion and public doses and environmental impacts, and to ensure that adequate up to date information is available to support decisions on emergency countermeasures.

Organisational Issues

800 As noted above, in Japan there were clear shortcomings in the implementation of relevant safety standards and guidance on protection against external hazards. This has fed criticism of the independence of the nuclear safety regulator and its links with government departments responsible for promoting nuclear power. The NSC located in the Japanese Cabinet Office provides high level supervision of the Nuclear and Industrial Safety Agency (NISA) which reported directly to the Ministry of Economy, Trade and Industry (METI).

801 It has now been reported that the Japanese government has agreed to establish a new nuclear safety regulatory body that will combine the functions of both the NSC and NISA, which may report instead to the Environment Ministry. The new body is expected to be fully operational by April 2012.

802 The effective independence of nuclear safety regulators, especially from bodies and organisations responsible for the promotion or utilisation of nuclear power, is regarded internationally as crucial for effective nuclear safety regulation. The Convention on Nuclear Safety (CNS) and the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (JCNS), both contain articles requiring Contracting Parties to ensure this independence. A European Union Council Directive of 25 June 2009 has built upon this in Article 5 which requires member states to:

“ensure that the competent regulatory authority is functionally separate from any other body or organisation concerned with the promotion, or utilisation of nuclear energy, including electricity production, in order to ensure effective independence from undue influence in its regulatory decision making”.

Of course, undue influence may come from other directions, for reasons that may be unconnected with the promotion or utilisation of nuclear power.

803 The UK Government has recently established HSE’s former Nuclear Directorate as the Office for Nuclear Regulation, currently a non-statutory agency of HSE. It intends to bring forward legislation in the future to create a new statutory body responsible for regulating the nuclear industry, which will be outside of HSE. In doing so, the Government will ensure that the legislation is consistent with the legal requirements of the European Union and the UK’s obligations under International Conventions. The Government may also use this opportunity to ensure that the statutory ONR is seen to have regulatory independence by its stakeholders. In this respect it is important to ensure

that regulatory decision making is proof against undue influence, and that ONR is able to operate in an open and transparent manner. This was covered in our Interim Report by Conclusion IR-3, viz:

Conclusion IR-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.

This conclusion is reinforced by the more recent information we have received concerning the Japanese regulatory system.

804 The intention is that the responsibility for final regulatory decisions – granting of nuclear site licences and attaching conditions to them – will be embodied in the statutory post of Chief Nuclear Inspector. This should ensure that regulatory decisions are made on the basis of the highest technical judgement, and demonstrably free from influence.

805 Recommendation IR-4 of the Interim Report reflected the importance of openness and transparency to both the nuclear industry and ONR in their efforts to build relationships with the public and other stakeholders. This will also be key to the statutory ONR demonstrating its independence to stakeholders.

Recommendation FR-8: The Government should consider ensuring that the legislation for the new statutory body requires ONR to be open and transparent about its decision-making, so that it may clearly demonstrate to stakeholders its effective independence from bodies or organisations concerned with the promotion or utilisation of nuclear energy.

806 We note below the intention to hold a special review meeting of CNS along with other international initiatives. The objectives of CNS, which was adopted by the UK in 1994, are to:

- To achieve and maintain a high level of nuclear safety worldwide through the enhancement of national measures and international co-operation including, where appropriate, safety-related technical co-operation.
- To establish and maintain effective defences in nuclear installations against potential radiological hazards in order to protect individuals, society and the environment from harmful effects of ionising radiation from such installations.
- To prevent accidents with radiological consequences and to mitigate such consequences should they occur.

807 The accident at Fukushima-1 indicates that international activities to secure these objectives have not been sufficiently effective. The IAEA action plan noted earlier is part of the initiatives to address such matters. The UK has done much to support international work in the past and should continue to do so.

Recommendation FR-9: The UK Government, nuclear industry and ONR should support international efforts to improve the process of review and implementation of IAEA and other relevant nuclear safety standards and initiatives in the light of the Fukushima-1 (Fukushima Dai-ichi) accident.

Research

- 808 To ensure nuclear safety and security in the UK, we need sufficient numbers of highly trained professionals. To this end, the Government is working with Cogent, the National Skills Academy for Nuclear, and the industry to ensure that the UK has a clear, jointly shared understanding of the key skills priorities for the nuclear sector, and how skills demand can be met. This includes the ability to carry out necessary safety and security related nuclear research.
- 809 ONR does not undertake its own research; rather it places contracts with specialist providers and supports research undertaken by other organisations, both in the UK and overseas, e.g. IAEA, and the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD).
- 810 The main vehicle used by ONR to take forward research is the Nuclear Research Index (NRI) which represents a co-ordinated view from the Regulator and the industry of what emerging research is needed to support existing nuclear facilities. The reactor operators use this to inform their nuclear research strategies. Research areas that are not addressed via the licensees' nuclear research strategies are addressed through research commissioned by ONR, with the costs recovered by a levy on the licensees. Although the NRI has provided a useful vehicle for taking forward safety-related research, the programme has been limited to existing nuclear facilities and apart from human factors, largely to technical research projects.
- 811 This report highlights a number of areas where new research is needed, including research around societal matters. We therefore need to ensure that the mechanisms we have in place to identify and implement research needs, in particular the NRI, are sufficiently flexible to accommodate both research identified so far, and research areas that have yet to come to light. As with other nuclear safety matters, the primary responsibility for undertaking necessary nuclear safety research lies with the nuclear industry. These considerations have highlighted the need for strategic overview of safety and security research and expertise in the UK and we therefore recommend that further work is undertaken in this area.

Recommendation FR-10: ONR should expand its oversight of nuclear safety-related research to provide a strategic oversight of its availability in the UK as well as the availability of national expertise, in particular that needed to take forward lessons from Fukushima. Part of this will be to ensure that ONR has access to sufficient relevant expertise to fulfil its duties in relation to a major incident anywhere in the world.

Interim Report Conclusions and Recommendations

General

- 812 Our Interim Report and its conclusions and recommendations were published in May 2011. Given the nature of the recommendations and the relatively short intervening period, we anticipated that at this point the industry would still be at the stage of developing plans and projects to address them. We have met with licensees to confirm this and although, as expected, none of the responses to the recommendations have yet been completed – with the exception of Recommendation IR-26 – an appropriate degree of progress is evident. As the licensees complete their reviews, which are being co-ordinated through the industry's Safety Directors Forum (SDF),

we anticipate that the resulting proposals for actions on-site, e.g. plant modifications, provision of additional off-site emergency equipment, and modifications to procedures and training will feed into their normal business processes for delivery. Going forward, beyond this report, we will continue to monitor and interrogate licensees' implementation of their plans as part of our normal regulatory processes and, as noted above, will report in about 12 months time.

- 813 The Interim Report drew 11 conclusions and made 26 recommendations on the basis of the information then available and our preliminary analysis of the Fukushima accident. In this Final Report we review these in light of the additional information available about the accident, supplemented by various submissions, and our further analysis. This has reinforced and added further substance to the Interim Report conclusions and recommendations. We therefore conclude that:

Conclusion FR-5: The additional information we have received since our Interim Report, and our more detailed analysis, has added further substantiation to, and reinforced, our initial conclusions and recommendations.

- 814 We have described the positive responses from Government, industry and Regulators earlier in this report, and commented favourably on the programmes of work initiated. This is in line with a national commitment to a positive safety culture. We therefore conclude:

Conclusion FR-6: The Industry and others have responded constructively and responsibly to the recommendations made in our interim report and instigated, where necessary, significant programmes of work. This shows an on-going commitment to the principle of continuous improvement and the maintenance of a strong safety culture.

- 815 This reinforces Conclusion IR-2 from our Interim Report and reflects the priority that we give to the maintenance and enhancement of safety culture in the industry. The Japanese government's report identified the need for a strong safety culture as a key "lesson" to be learnt from Fukushima. This is an area where we will continue to devote considerable attention as part of our on-going regulatory strategy, indeed it is at the heart of our business plan.

- 816 In this report we have reviewed various aspects relating to human performance and recognised the usefulness of the work undertaken by the UK's National Skills Academy for Nuclear. We believe that it is vital to instil an enhanced sense of "nuclear professionalism" as part of a wider approach to promoting high levels of nuclear safety culture in all those who work in the nuclear sector. This applies especially with the entry of new corporate players and increasing numbers of new recruits coming into the UK nuclear industry. Given the lessons identified in this area, particularly by the Japanese government's report, and our continued commitment to promoting high levels of safety culture, we introduce a new recommendation.

Recommendation FR-11: The UK nuclear industry should continue to promote sustained high levels of safety culture amongst all its employees, making use of the National Skills Academy for Nuclear and other schemes that promote "nuclear professionalism".

Specific Conclusions and Recommendations from the Interim Report

817 We have held discussions with various parties on the Interim Report conclusions and recommendations, reviewing progress and plans, and have reflected on the additional information acquired. In doing this we have been able to clarify our expectations in regarding responses to key recommendations, as discussed below, where we also note progress and additional supporting information.

Recommendation IR-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.

818 Various discussions have been held with senior staff of IAEA and others and we expect that this recommendation will be progressed through the development of the IAEA action plan, noted above. We will be monitoring such developments and incorporating relevant aspects into ONR emergency arrangements.

819 In the event of a severe nuclear accident, there are essentially two types of information necessary to allow other countries to provide authoritative advice on actions needed to protect their nationals, particularly those in the country suffering the accident. The first is basic data about the reactor design including reactor type, containment, thermal power, protection systems, operating history and inventory and condition of any nuclear materials, such as spent fuel, stored on the site. Apart from recent operating history, this information would not change significantly over short to medium timescales. To minimise demands on the operator of the affected plant, such information should be held permanently by a central source maintained on behalf of the international community, noting the need to ensure data provenance and access control.

820 The second is information on accident progression and the prognosis of its further development. As may be seen from the Fukushima accident, conditions on the affected site may make it difficult, if not impossible, to obtain all necessary data. The operator's priority in this respect would be to provide such information as is available to its national authorities, while at the same time trying to restore control on the site. This suggests that mechanisms for communicating this information between national governments should be streamlined and strengthened, with international agreement on the type of information that needs to be provided and its routing. Again this could be through a central point, to ensure consistency and minimise burdens on the source of the information.

821 It was noted in the Interim Report that we would provide an update on relevant changes to international arrangements in this Final Report. We attended the triennial review meeting of CNS^{****} where it was determined that, in response to the Fukushima accident, a special review meeting should be held in summer 2012. At this meeting national responses to the Fukushima accident, including the acquisition of information and the provision of advice, will be subject to peer review by other signatories to the Convention. A number of special meetings on Fukushima have been held by various international bodies and organisations, such as OECD-NEA and the G8 group of countries, although as yet there are no specific new international arrangements to report. However, new arrangements may well result from the IAEA action plan, which is to be discussed by

^{****} The CNS review meeting is a peer review process amongst signatory countries to ensure compliance with the Convention articles, which cover a range of nuclear safety topics. The UK is a signatory.

its governing board in September 2011. The action plan is based on discussions and presentations at the Ministerial Meeting convened by IAEA in June 2011, with further input from the International Nuclear Safety Advisory Group (INSAG), of which the ONR HM Chief Inspector of Nuclear Installations is a member.

Recommendation IR-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.

- 822 As noted, ONR has already started a project to review lessons from the Fukushima-1 accident for its SAPs and TAGs which is expected to conclude next year. However, as discussed earlier, we have already identified some areas in which we consider that they should be further developed and clarified.

Recommendation IR-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.

- 823 The Interim Report noted the vital role of communications and data acquisition in implementing an effective emergency response, and this is discussed earlier in this Discussion section. However, our earlier comments on Recommendation IR-1 regarding the sourcing of international information may also be applied to the UK’s national emergency arrangements, as noted in the Interim Report. ONR’s capability to monitor and assess a licensee’s actions in the event of a severe accident in the UK, and to advise the authorities responsible for off-site public protection, would be enhanced by ready access to relevant plant information and current plant monitoring data. Our review therefore considers the type and scope of information that ONR would need to meet its responsibilities in the event of a severe accident, as well as potential systems for acquiring it. It is anticipated that basic plant data held by ONR, and that which we suggest should be held by an international organisation under Recommendation IR-1, would have much in common.

- 824 The licensee is responsible for managing the on-site response to an incident or accident, so ONR’s information needs would be a sub-set of those of the licensee. However, as noted in the Interim Report (paragraph 362), current information on the status of critical safety functions, i.e. the control of criticality, cooling and containment, and releases of radioactivity to the environment, would greatly enhance ONR’s ability to provide independent advice to the authorities in the event of a severe accident.

Recommendation IR-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.

- 825 The earthquake and tsunami not only led to extensive damage to infrastructure around the Fukushima-1 site, including disconnection of the site from the electricity grid and damage to transportation, but also caused damage to essential supplies and services on the site. This included

damage to diesel storage tanks, electrical switchgear, batteries and electronic dosimeters. We therefore consider that the industry's review of the dependency of nuclear safety on off-site infrastructure should embrace essential supplies such as food, water, conventional fuels, compressed gases and staff, as well as the safe off-site storage of any equipment that may be needed to support the site's response to an accident. Consideration should also be given to the timescales required to transfer supplies or equipment to site. This implies a wider consideration of the site's self-sufficiency than just the provision of electrical supplies. We are pleased to note that the industry has independently come to the same conclusion and is undertaking broader reviews under the heading of "on-site resilience".

Recommendation IR-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.

826 The report of the IAEA mission to Japan provides for a better understanding of the events at the two Fukushima sites. In particular, the Fukushima-2 site was not inundated by the tsunami to the extent that the Fukushima-1 site was, one grid connection remained available, as did several emergency diesel generators and electrical switch gear, and other safety-related equipment remained operational. This said, the Fukushima-2 site still suffered significant disruption to its safety-related systems, including cooling by the ultimate heat sink, and some of the switchgear. However, the site management was able to provide ad-hoc arrangements to secure effective cooling of the reactors, in particular laying 9km of temporary heavy electrical power cabling in 16 hours to connect available switch gear to vital equipment.

Conclusion IR-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 IR-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.

827 Some have commented on these alongside the information that was provided in Annex F of our Interim Report. [Annex F](#) and [Annex G](#) of this Final Report provide further details of flooding risks at UK nuclear licensed sites and this Discussion section provides more information on methodology. Strategic level information is held by the environment agencies while site-specific flooding risks are part of the licensees' safety cases, and a review of these is provided in [Annex G](#). This review confirms the adequacy of the present site-specific cases and the methodology used. Protection of nuclear sites from flood risks is already a well established part of ensuring safety at nuclear sites. However, it is important to learn any lessons from the Fukushima accident and for the industry to review flooding studies in line with the principle of continuous improvement.

Recommendation IR-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.

- 828 Although this recommendation specifically addresses new spent fuel strategies, we nonetheless expect existing licensees to continue to review their current spent fuel strategies as part of their periodic review processes, and to make any reasonably achievable improvements. We are mindful that any intended changes need to take account of wider strategic factors including the implications for the nuclear fuel cycle.
- 829 The information since our Interim Report has indicated that the issues relating to spent fuel stored in Reactor Building 4 were not as severe as originally thought, such that it appears that there was no significant deterioration of the spent fuel. This may be thought as weakening the need to pursue Recommendation IR-12 with due diligence. That is not our view as during the early days of the accident there was significant concern about spent fuel in the reactor buildings at Fukushima-1. Additionally, considerable and novel efforts had to be applied to ensure it was kept safe.
- 830 There were fewer problems with the common spent fuel pond and dry cask store at Fukushima-1, and the IAEA mission team were able to visit both these facilities to confirm their status. In the case of the dry cask store the team observed that while the store was inundated with sea water to a height of around 10m, the spent fuel casks remained intact. Similarly, no significant problems were observed with the common spent fuel storage facility. Some have highlighted spent fuel as a significant issue arising out of the Fukushima accident and noted issues related to reprocessing and the holding of high level waste. From our review of the information about Fukushima we do not identify any additional issues about reprocessing or high active waste storage beyond those general ones discussed elsewhere in this report. Comments have also been received about the long-term storage of spent fuel from any new build reactors as well as spent fuel storage at Sizewell B. Such issues would be the subject of our normal consideration of the respective safety cases for such facilities and are not part of this report.

Recommendation IR-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.

Recommendation IR-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.

- 831 We have linked these two recommendations in this review given their related aspects. Although such extreme events have a very low assessed probability of occurrence, we believe that the industry should consider how it might respond and manage its plant in extreme circumstances. The combination of these two recommendations means that we would expect industry to identify potential strategies and contingency measures for dealing with situations in which the main lines of defence are lost. Considerations might include, for example, the operator's capability to undertake repairs and the availability of spare parts and components. As indicated in Interim Report

Recommendation IR-22, capability includes the availability of personnel trained in the use of emergency equipment along with necessary supporting resources.

- 832 Additionally, we expect the UK nuclear industry to consider the optimum location for portable emergency equipment, so as to limit the likelihood of it being damaged by any external event or the effects of a severe nuclear accident. The implication of potential initiating events for the transportation of such equipment is another important consideration. Because of the possibility for high radiation levels on site, consideration should also be given to the need for remotely controlled equipment including valves. Furthermore, the consideration of layout should also include the effective segregation and bunding of areas where radioactive liquids from accident management may accumulate.
- 833 Regarding other aspects of Recommendation IR-25, the industry needs to ensure it has the capability to analyse severe accident progression to the extent necessary to properly inform and support on-site severe accident management actions and off-site emergency planning. This may require further research and modelling development, particularly for nuclear facilities that have not already benefited from international severe accident research programmes. It also needs to ensure that sufficient severe accident analysis has been performed for all facilities with the potential for accidents with significant off-site consequences, in order to identify severe accident management and contingency measures. Such measures must be implemented where reasonably practicable by staff trained in their use.
- 834 There is also a need for the industry to adopt a systematic, analytical approach to developing an understanding of the risks presented by severe accidents. This is addressed earlier in this Discussion section under "[Accident Mitigation](#)".
- 835 The industry's reviews should also examine how the continued availability of sufficient on-site personnel can be ensured in severe accident situations, as well as considering how account can be taken of acute and chronic stress at both an individual and team level. This is therefore linked in with Recommendation IR-24 which stated:

Recommendation IR-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.

- 836 It is noted that this is a wide ranging recommendation and there are a number of aspects that bear further elaboration. These are noted below:
- The reviews need to acknowledge design differences between individual nuclear installations and consider whether corporate Severe Accident Guidelines (SAG) need to be customised.
 - Adequacy of personnel numbers for long-term emergencies, particularly for multi-unit sites ,and taking into account the potential impact of infrastructure damage on the ability to mobilise large numbers of personnel.
 - The time windows for availability of off-site support may be challenged, hence the role of on-site personnel may change, which has implications for procedures and training.

- The review of Severe Accident Management Guidelines (SAMG) should consider not only critical safety functions prioritisation, but also whether and how SAMGs support any dynamic re-prioritisation based on emerging information.
- Consideration should also be given to operator support requirements relating to tactical and strategic decision making.
- In addition to the acute phase of a severe accident, consideration also needs to be given to stabilisation, recovery and clean-up, and the personnel involved from the many organisations involved.

Recommendation IR-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.

- 837 This recommendation is more specific and was based on a perceived vulnerability of spent fuel in the Fukushima-1 storage ponds to loss of cooling water. This derived from limited early information on problems experienced in Reactor Building 4, although more recent information indicates that the spent fuel in the on-site storage ponds may not have suffered significant damage due to loss of cooling. While the recommendation is still valid, the more recent information places it in the broader context of the need for all safety-related plant associated with spent fuel ponds to be designed to withstand internal and external hazards to standards consistent with the rest of the nuclear facility.

Recommendation IR-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.

- 838 The industry focus with respect to this recommendation should be on future studies regarding the continuing validation of methodologies for analysing the seismic performance of Structures, Systems and Components (SSC) important to safety. This should include concrete structures as well as those fabricated from other materials.

Recommendation IR-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.

- 839 The link between this and Recommendation IR-8 is now explicitly recognised, and both should be considered by the industry within the wider context of “on-site resilience”.

Fuel

840 The Interim Report provided a conclusion any lessons related to the use of Mixed Oxide (MOX) fuel in Reactor Unit 3, viz:

Conclusion IR-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.

841 In the information we have reviewed since the Interim Report and from our further analysis there is nothing so far to suggest that any significant health effects have arisen from the use of MOX fuel. Some have questioned whether there would be some on-site implications for the operators dealing with it. This is unlikely to be the case given the dominating isotopes in fuel used in a reactor. Questions have been raised about the possible use of MOX fuel in reactors in the UK. We have yet to see a safety case for such use and the information to date about Fukushima-1 does not add to knowledge about the safety of the use of MOX.

842 The Interim Report raised the question of the adequacy of on-site emergency provisions and recommended that they be reviewed:

Recommendation IR-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.

843 We note above how this recommendation is linked in with others, in particular that special consideration needs to be given to the resources needed to support intervention personnel in severe accidents. Consideration of communication in severe accident conditions needs to take into account any special protocols. This recommendation should be considered in the light of the capability and potential enhancement of Alternative Indication Centres (AIC) already in place at UK plants following learning from the Three Mile Island event in 1979.

844 The Interim Report noted that, at the time it was finalised, we had little information on whether there were alternative emergency control centres available to the operators at Fukushima-1. We now know from the report of the IAEA fact-finding mission that, following an earthquake in 2007 that affected the Kashiwazaki-Kariwa nuclear power plant, the Fukushima-1 site had been equipped with a seismically robust building housing the site emergency response centre. This building was not only built to withstand earthquakes but had adequate provisions to ensure its habitability in the event of a radiological release. The building was provided with limited communication facilities with on-site plant control rooms as well as with external agencies, such as TEPCO headquarters in Tokyo.

845 The IAEA mission recognised the benefit of these arrangements and drew lessons from them to the effect that nuclear sites should be provided with adequate on-site seismically robust, suitably shielded, ventilated and well-equipped buildings to house emergency response centres, and should have available, as far as practicable, information on essential safety-related parameters based on hardened instrumentation lines. They should also have sufficient secure communication lines to control rooms and other places on-site and off-site.

846 The extent of the threat presented by earthquakes and other external hazards varies geographically and this should be accounted for in the design basis of a nuclear facility. For example, it would be disproportionate to design a plant in a region of low seismicity for the same ground movement as one in an area of high seismicity. However, we endorse the basis for the IAEA mission lessons regarding the need for robust functionality for command and control in severe conditions and we have introduced two new recommendations under "[Accident Mitigation](#)" earlier in this Discussion section.

Recommendation IR-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.

847 In addition to impacting communications, it is possible that extreme external events could also affect off-site centres used to support the site in an emergency. Alternative locations should be available for such centres and they should be capable of being commissioned in an appropriate timescale.

Stress Tests

848 Following the Fukushima accident, the Council of the European Union proposed that nuclear power plants in European Union member states should be subject to "Stress Tests" and asked the European Nuclear Safety Regulatory Group (ENSREG) to develop a technical specification for them. The ENSREG specification was adopted by the European Council on 26 May 2011, and is reproduced in [Annex H](#).

849 ENSREG and the European Commission agreed that licensees, who bear the responsibility for safe operations, would be responsible for undertaking the analyses required and that these should begin by 1 June 2011. Licensees are required to report these analyses and their conclusions to their national regulators, who are in turn responsible for independently reviewing them and reporting their conclusions to ENSREG and the European Commission. ONR submitted a national report on progress by the due date of 15 September 2011. Following submission of the final national reports by the end of December 2011, these will be peer reviewed by a team of nuclear safety regulators jointly agreed by ENSREG and the European Commission.

850 The "Stress Tests" require licensees to examine the safety margins of nuclear power plant with particular reference to the circumstances and issues arising from the Fukushima accident. They consequently complement the recommendations of our Interim Report. ONR will independently assess the results of the "Stress Tests" and require the licensees to undertake any reasonably practicable improvements. In the UK, the scope of the "Stress Tests" has been widened by ONR to include non-NPP licensed nuclear facilities and they are expected to address site-wide services and infrastructure as part of this process. The "Stress Test" reports from these non-reactor plant licensees do not have to be submitted to ENSREG or the European Council.

Way Forward

851 There are overlaps between the "Stress Tests" outcomes and the recommendations in our reports. Hence the nuclear industry will, no doubt, produce a common plan for responding to the "Stress

Tests” as well as the recommendations in this report. In line with our drive for greater openness and transparency, we expect this plan to be published.

- 852 The outcome of work to meet our recommendations and the outcomes from the “Stress Tests” should be published along with proposals for any reasonably practicable improvements to plant, people or procedures that may emerge.
- 853 Given the timescales for the “Stress Tests” and the full response to our recommendations, we have decided to produce a further report in about a year’s time which will provide an update on progress in implementing the lessons for the UK’s nuclear industry.

ANNEX A: INTERNATIONAL CO-OPERATION

- 1 The Secretary of State's (SoS) 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 Organisation for Economic Co-operation and Development's (OECD) Nuclear Energy Agency (NEA) (www.oecd-nea.org)
 - European Council's European Nuclear Safety Regulators Group (ENSREG) (www.ensreg.org)
 - The Western European Nuclear Regulators' Association (WENRA) (www.wenra.org)Further information on the above bodies is available via their websites.
- 2 All have had meetings (or plan meetings in the near future) at which the Fukushima 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 (CNS) was held and special attention was paid to the topic of this report as reported at www-ns.iaea.org/conventions/nuclear-safety. ONR staff play an active part in these organisations, including HM Chief Inspector of Nuclear Installations, see [Annex E](#).
- 3 In addition, the Office for Nuclear Regulation (ONR) has close bilateral links with other nuclear regulators, in particular the United States Nuclear Regulatory Commission (US NRC) and the French Autorité de Sûreté Nucléaire (ASN). These links have been very useful in the immediate response to the accident and in co-ordinating work.
- 4 HM Chief Inspector of Nuclear Installations has also had bilateral discussions with several other chief nuclear regulators from around the world and with the Director Generals and senior staff of IAEA and NEA, and similarly with the Director General for Energy of the European Council.
- 5 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 "Stress Tests" (latest version is available on the WENRA website (www.wenra.org)) for nuclear facilities in Europe, based on the emerging issues and 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 2011.
 - A ministerial conference under IAEA later in June 2011.
 - An extraordinary Review Meeting of the Convention on Nuclear Safety to review contracting parties' responses to the Fukushima accident in late 2012.
- 6 Additionally, HM Chief Inspector of Nuclear Installations was 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 will continue.
- 7 Such co-operation has greatly enhanced our ability to respond to the Fukushima 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: www.hse.gov.uk/risk/theory/r2p2.pdf (Ref. 4).

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 / 1995-98 / 1999 ⁽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 and Safety Statistics (1996 / 97, 1997 / 98, 1998 / 99 and 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 / 97-1999 / 2000 ⁽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 / 2000 ⁽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 the assumption of 3 million dives per year. British Sub-Aqua Club (2001)
 - (4) Based on an 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)

Following the provision the Interim Report by HM Chief Inspector of Nuclear Installations on 18 May 2011, a House of Commons Energy and Climate Change Committee on 9 June 2011 took evidence from the Chief Inspector on various matters related to the Interim Report. This included discussions about risks from nuclear power and other energy sources. The Chief Inspector offered to supplement his oral evidence with a technical note. A paper (*A Comparison of Risk Levels for Different Sources of Energy, ONR Technical Note ONR-FR-TN-003, Revision 0*) fulfilling that obligation was produced and can be found on our website www.hse.gov.uk/nuclear/reports.htm.

ANNEX C: TYPICAL EXPOSURES TO IONISING RADIATION FROM DIFFERENT ACTIVITIES

Table C1: Typical Exposures to Ionising Radiation from Different Activities

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

Figures taken from the Health Protection Agency (HPA) website (www.hpa.org.uk).

It should be noted that people may make different judgements on the tolerability of certain levels of exposure to radiation depending on various factors such as, what they perceive benefits to be, whether they consider it is a voluntary exposure to radiation, what alternatives there are etc.

ANNEX D: EMERGENCY ARRANGEMENTS IN THE UK

International Conventions and Agreements

- 1 The Convention on Early Notification in the Event of a Nuclear Accident or Radiological Emergency (Ref. [D1](#)) describes the arrangements established by the International Atomic Energy Agency (IAEA) under which any signatory country that operates nuclear installations is obliged to inform 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.
- 2 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

- 3 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. [D2](#)).
- 4 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 1974 (HSWA74) (Ref. [D3](#))
 - Radiation (Emergency Preparedness and Public Information) Regulations 2001 (REPPiR) (Ref. [D4](#))
 - Civil Contingencies Act 2004 (CCA) (Ref. [D5](#))
 - Nuclear Installations Act 1965 (as amended) (NIA65) (Ref. [D6](#))
 - Ionising Radiation Regulations 1999 (IRR99) (Ref. [D7](#))
- 5 To co-ordinate 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.
- 6 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. [D8](#)) for planning for a civil nuclear emergency. NEPLG also reviews results of off-site emergency exercises to ensure that important lessons are learnt from those exercises and put into practice.

Emergency Planning Principles

- 7 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. [D9](#)). 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 recovering from emergencies whatever the scenario.
- 8 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.
- 9 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

- 10 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

- 11 HPA was established on 1 April 2005 under the Health Protection Agency Act 2004 (Ref. [D10](#)) 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.
- 12 The HPA Centre for Radiation, Chemical and Environmental Hazards (CRCE) 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.
- 13 HPA-CRCE 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.

- 14 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).
- 15 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.
- 16 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.
- 17 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.
- 18 HPA's CRCE is undertaking a project to update and consolidate its advice on radiation emergencies and recovery. Two of NRPB's publications (NRPB, 1990, Ref. [D11](#) and NRPB, 1997a, Ref. [D12](#)) gave general advice on ERLs, 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. [D13](#)) 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.
- 19 In 2007, the International Commission on Radiation Protection in its Publication 103 (ICRP, 2007, Ref. [D14](#)) 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. [D15](#)) and for existing exposure situations in Publication 111 (ICRP, 2009, Ref. [D16](#)). 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.
- 20 HPA will be updating and consolidating its advice, and this will include making recommendations on the future use of ERLs, the role of averted and residual dose, withdrawal of emergency countermeasures and the development of a recovery strategy, and consideration of the issues presented by long-duration releases.

Organisation

- 21 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 Co-ordinating Centre (SCC), and the organisation of the nuclear emergency briefing rooms in London and Scotland.

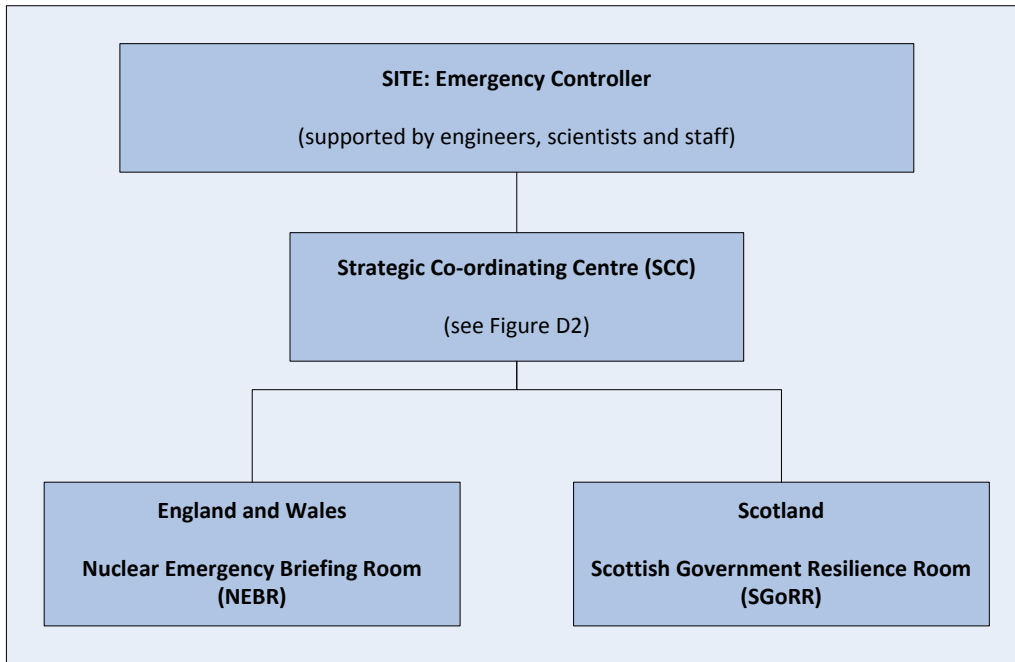


Figure D1: Interface between National, Local and Site Responders

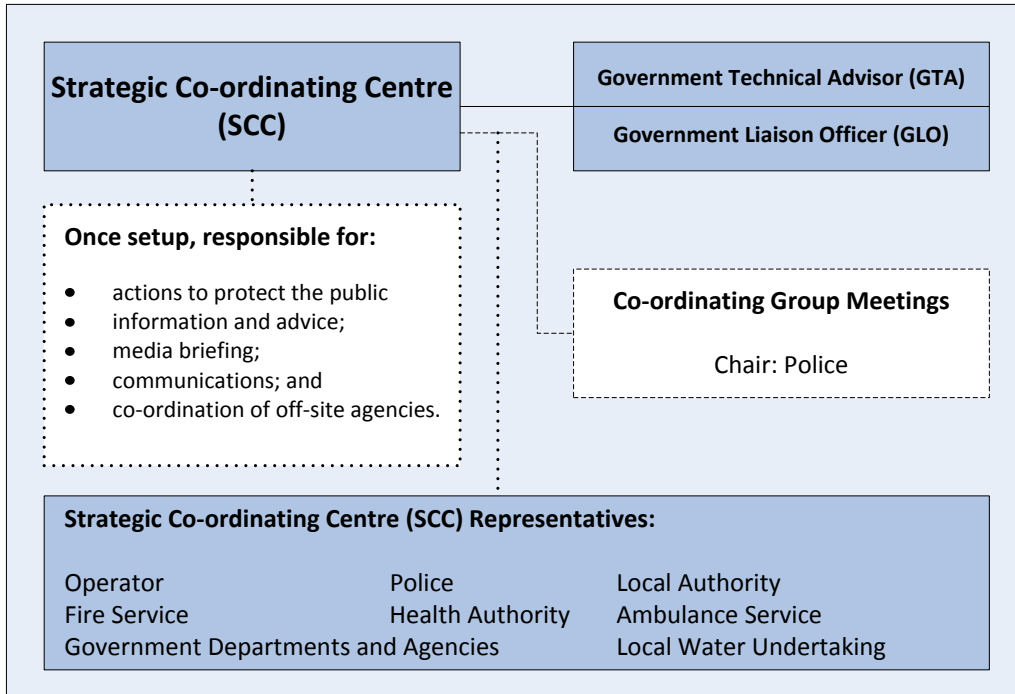


Figure D2: Organisation at Strategic Co-ordinating Centre

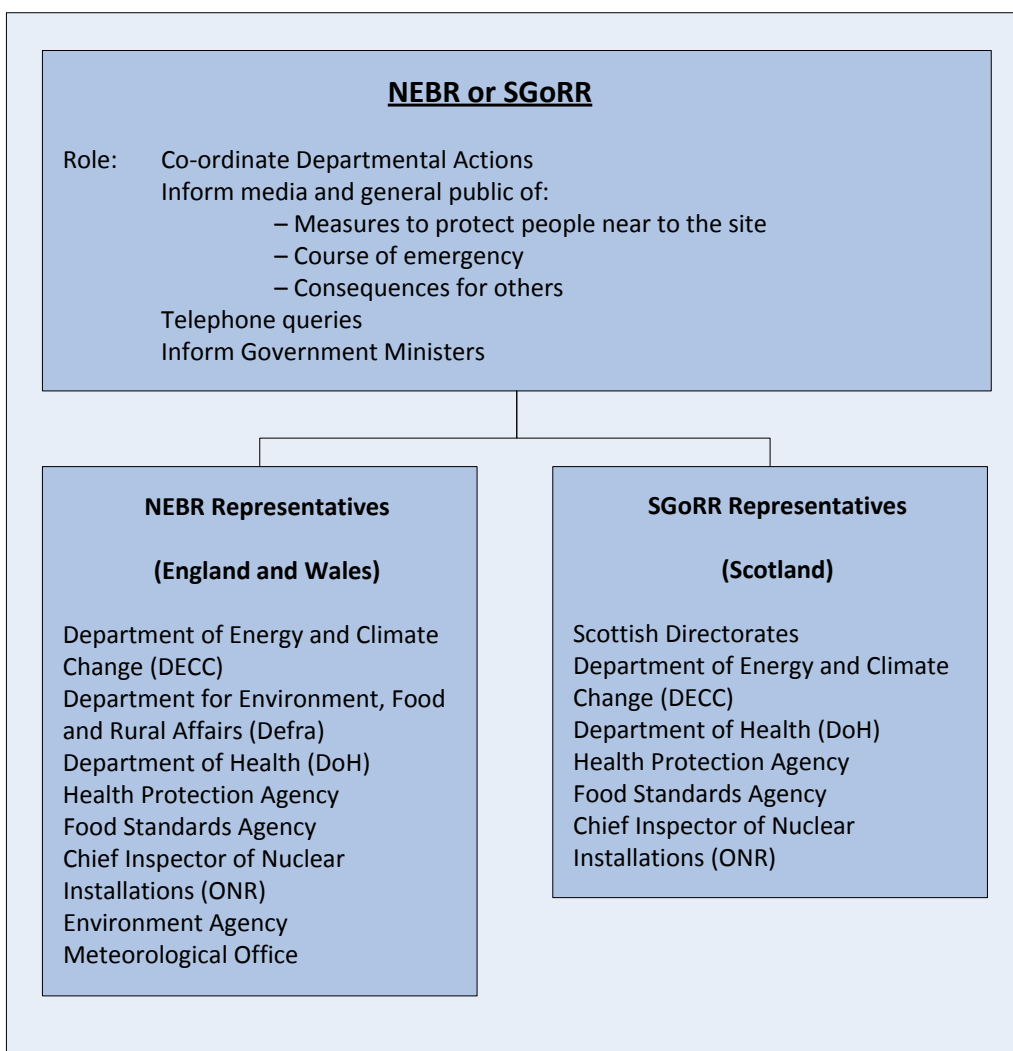


Figure D3: Organisation at Nuclear Emergency Briefing Room (NEBR) and Scottish Government Resilience Room (SGoRR)

National Co-ordinating Authority

- 22 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 [D17](#) and [D18](#)).
- 23 DECC co-ordinates emergency nuclear 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

- 24 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 co-ordinate 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

- 25 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".
- 26 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.
- 27 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 NIA65 (Ref. [D6](#)) and REPPIR (Ref. [D4](#)). These are both regulated by ONR.

Training, Drills and Exercises

- 28 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. [D4](#)).
- 29 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.
- 30 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

- 31 Lessons learnt 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.

References

- D1 *Convention on Early Notification in Case of a Nuclear Accident or Radiological Emergency* Adopted on 26 September 1986, at the 8th, plenary meeting Legal Series No 14 IAEA Vienna (1986)
- D2 *Preparedness and Response for a Nuclear or Radiological Emergency* IAEA Safety Standards Series No. GS-R-2 IAEA 2002
- D3 *Health and Safety at Work etc. Act 1974 (1974 c.37)* ISBN 0-10-543774-3
www.hse.gov.uk/legislation/hswa.htm
- D4 *Radiation (Emergency Preparedness and Public Information) Regulations 2001* SI 2001 No 2975
www.legislation.gov.uk/nisr/2001/436/contents/made
- D5 *Civil Contingencies Act 2004* www.opsi.gov.uk/acts/acts2004/Ukpga_20040036_en_1.htm
- D6 *Nuclear Installations Act 1965 (as amended) (1965 c.57)* ISBN 0-10-850216-3
www.legislation.gov.uk/ukpga/1965/57/contents
- D7 *The Ionising Radiations Regulations 1999* www.legislation.gov.uk/uksi/1999/3232/contents/made
- D8 *Nuclear Emergency Planning Liaison Group Consolidated Guidance* May 2008
webarchive.nationalarchives.gov.uk/http://www.berr.gov.uk/whatwedo/energy/sources/nuclear/key-issues/emergency/neplg/guidance/page18841.html
- D9 *Emergency Response and Recovery: Non statutory guidance to complement Emergency Preparedness* HM Government November 2005
- D10 *Health Protection Agency Act 2004* www.legislation.gov.uk/ukpga/2004/17/contents
- D11 *Emergency Reference Levels of Dose for Early Countermeasures to Protect the Public* National Radiological Protection Board Document NRPB 1 (4), 5-33 1990
- D12 *NRPB (1997a) Application of Emergency Reference Levels of Dose in Emergency Planning and Response* National Radiological Protection Board Document NRPB, 8 (1), 21-34 1997
- D13 *NRPB (1997b) Intervention for Recovery after Accidents.* National Radiological Protection Board Document NRPB, 8 (1), 1-20 1997
- D14 *The 2007 Recommendations of the International Commission on Radiological Protection* ICRP Publication 103 International Commission on Radiological Protection 2007
- D15 *Application of the Commission's Recommendations for the Protection of People in Emergency Exposure Situations* ICRP Publication 109 International Commission on Radiological Protection 2008
- D16 *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 International Commission on Radiological Protection 2009

- D17 *Central Government Arrangements for Responding to an Emergency, Concept of Operations 31* March 2005
- D18 *The Lead Government department and its role - Guidance and Best Practice* Cabinet Office March 2004

ANNEX E: ONR INVOLVEMENT IN THE CONVENTION ON NUCLEAR SAFETY

- 1 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"), s. 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.
- 2 Article 5 of the Convention (Ref. [67](#)) 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."
- 3 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.
- 4 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

- 1 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 of Nuclear Installations about flood risks around UK nuclear sites, and consideration of UK tsunami risks in the light of the events in Japan.
- 2 The purpose of this annex is to:
 - provide a 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; and
 - summarise the roles of the environment agencies in this area.

The Role of the Environment Agencies

- 3 SEPA and the Environment Agency are the principal flood risk management authorities. They provide a strategic overview role relating to all forms of flood risk. In England and Wales, the local planning and delivery of some forms of flood management is also provided by local authorities, internal drainage boards, sewerage companies and highway authorities.
- 4 Responsibility for managing flood risk in Scotland is shared across a number of bodies in addition to SEPA: Local authorities, Scottish Water and the Scottish Government all play a role.
- 5 In their overarching role, SEPA and the Environment Agency are responsible for forecasting and mapping flood risk, providing warnings, advising on development in the flood-plain, building and keeping defences in good order (except in Scotland where this falls to the local authorities) and taking part in emergency planning and response. The Environment Agency manages central government grants for capital projects carried out by local authorities and internal drainage boards.
- 6 The Environment Agency is the consenting authority for flood and coastal risk management and land drainage. Alongside their role as a flood management authority, SEPA is also the consent authority for works within the non-coastal water environment, where such works could adversely impact on natural water-bodies or on the objectives of the Water Framework Directive.
- 7 The environment agencies have regulatory responsibility for environmental permits relating to nuclear licensed sites and are statutory consultees on planning applications associated with nuclear licensed sites and will advise planning authorities where relevant.

Tsunami Risk and Hazard in the UK

- 8 The devastating tsunami in the Indian Ocean of December 2004 prompted the commissioning of a comprehensive study by the Department for Environment, Food and Rural Affairs (Defra) in 2005

(Ref. [F1](#)) into the threat posed by tsunami to the UK. The study considered possible tsunami sources in the following regions:

- UK coastal waters;
- North west European continental slope including submarine landslides;
- Plate boundary area west of Gibraltar;
- Canary Islands;
- Mid-Atlantic ridge;
- Eastern North America continental slope; and
- Caribbean.

9 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” (Ref. [F2](#)).

10 The 2005 Defra study modelled 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.

11 Two of these source origins were reviewed in more detail in the 2006 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.

12 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 heights of tsunamis recorded off the east coast of Japan where the recent event was the third major tsunami in little over a century (Ref. [F3](#)).

13 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 the Department for Energy and Climate Change (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. Notwithstanding the above, it is considered that a review of emergent data since the DEFRA work is a prudent activity.

- 14 The Environment Agency has, in its submissions, 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' supporting infrastructure.
- 15 Since the publication of the Defra report in 2006 there has been further research conducted into potential sources of tsunamis that might affect the UK including submarine landslides that may occur further north in the Arctic. Furthermore, it is not clear how climate change and sea level rise may affect the propagation of tsunami waves. Such considerations should be taken into account in any revision of relevant guidance and in reviews of site-specific flooding studies where appropriate.

Effects of Climate Change

- 16 Government has recently published its policy on adapting infrastructure to climate change (Ref. [F4](#)) 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 all sources of flood risk and is expected to increase coastal erosion rates, cliff stability and sea defence fragility. For those nuclear sites and infrastructure on the coasts, the impacts from sea level rise, change to storm surges and wave climate (wave heights, period and direction) 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 (Ref. [F5](#)) (Defra 2006) or its planned revision for English sites, and also demonstrate how the site can be managed and made safe against the latest^{§§§§} credible maximum climate change scenario for the site.
- 17 The credible maximum scenario is a peer-reviewed and robust worst case, but plausible, scenario for the site that 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 (Ref. [F6](#)). The revision to the 2006 Defra guidance will take account of the latest (UKCP09) projections, which include more information on uncertainty and the credible maximum approach.
- 18 A managed adaptive approach to flood and coastal erosion risk management in the face of extreme climate change (credible maximum) is used in the assessment of, and planning for future flood and coastal erosion risks. A managed adaptive approach is based upon the non-foreclosure of practicable adaptation options and then implementing those as appropriate if the operator or ONR were not confident that the flood risk protection could continue to be provided to the required standard. Continuous monitoring of the risk is an important part of the managed adaptive approach. This approach provides flexibility to manage future uncertainties associated with climate change.
- 19 The credible maximum climate change scenario should be used:

^{§§§§} In recognition of the fact that climate change predictions are likely to change over time as better science becomes available.

- 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; and
- 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

- 20 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 coastal change were provided in relation to nominated sites for new build, co-location also makes them applicable to existing facilities.
- 21 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:
webarchive.nationalarchives.gov.uk/20110302182042/https://www.energynpsconsultation.decc.gov.uk/nuclear/nominated_sites.

National Flood Risk Assessments

- 22 There are a number of nationally available datasets and assessments of flood risk. SEPA and the Environment Agency hold high-level information which can provide an indication of the potential for flooding to occur in areas around nuclear sites across England, Scotland and Wales from fluvial (river), coastal and surface water sources. While this is sufficient to provide a first indication of those areas potentially at risk of flooding, it is not sufficient to provide a detailed quantitative site assessment of the flood risks – this needs to be done through site-specific assessments. The available information may also be used to indicate potential impacts on supporting infrastructure such as road access/egress (see below) or transmission lines etc.
- 23 The following sub-sections provide more details of the type of information available.

Flood Map for Rivers and the Sea (England and Wales)

- 24 This information shows areas that could be impacted by flooding from the rivers or sea. The mapped outline does not take account of the presence of existing flood defences but it does show, where information is available, areas that would normally benefit from defences during a major flood, however, this does not consider the chances that a defence may fail.
- 25 The Flood Map for Rivers shows present day flood outline for flood events with a 1 in 100 (i.e. a flood with a 1% annual probability of occurrence) and 1 in 1000 (0.1% annual probability) chance of occurring in any year. The Flood Map for the Sea shows the present day flood outline for flood events with a 1 in 200 (0.5% annual probability) and 1 in 1000 chance of occurring in any year. The map does not take future climate change into account.
- 26 This information is normally used to help inform emergency and spatial planning and to provide a general awareness to the public of flooding from rivers and sea. It is a trigger for further

assessment to take place and is not suitable for use solely to understand risk at the individual property scale.

National Assessment of Flood Risk

- 27 The National Flood Risk Assessment (NaFRA) shows the likelihood of flooding across England and Wales taking into account the presence, condition and effect of flood defences. It was published in 2010 and has been updated, depending on risk, on an individual river catchment basis.
- 28 These flood likelihood data may be used to give an indication of areas of flood risk that may need further investigation. They do not indicate the likelihood of flooding to individual properties. It is not detailed enough at this stage for use in making site specific operational or management decisions and does not take future climate change into account.

Indicative River and Coastal Flood Map (Scotland)

- 29 The Indicative River and Coastal Flood Map (Scotland) is a national strategic assessment of flood risk to support planning policy in Scotland. The map provides a first indication of those areas of Scotland potentially at risk of flooding from watercourses or the sea. The Flood Map shows the 1 in 200-year flood event outline (i.e. the flood with a 0.5% chance of occurring in any given year) for present day flood risk, it does not account for the potential future effects of climate change.
- 30 The Indicative River and Coastal Flood Map (Scotland) has been produced following a consistent, nationally-applied methodology for catchment areas equal to or greater than 3km² using a Digital Terrain Model (DTM) to define river cross-sections and low-lying coastal land. The outlines do not account for flooding arising from sources such as surface water runoff, surcharged culverts or drainage systems. The methodology was not designed to quantify the impacts of factors such as flood alleviation measures, buildings and transport infrastructure on flood conveyance and storage.
- 31 Given the strategic nature of the Flood Map it is not designed to quantify the absolute risk to individual properties or locations but to raise awareness of flood risks issues for individuals, organisations and public authorities to trigger further detailed assessment where necessary.

Coastal Sea-levels

- 32 The Environment Agency, in partnership with SEPA, holds recently updated information on coastal conditions (e.g. sea-levels, surge and wave characteristics) around the coast of England, Wales and Scotland (Ref. [F7](#)). This information is available under licence.

Access / Egress

- 33 The potential impacts on access to, and egress from, sites formed part of the Environment Agency consultation response to the 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.
- 34 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:

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

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

Summary

- 36 Only strategic level flood risk information can be derived from existing data held by the Environment Agency and SEPA. It indicates whether there is the potential for flooding to occur in the wider areas around nuclear sites, but does not describe the *risk* to specific facilities. Detailed site specific flood risk assessments (for example those provided as part of planning applications or as part of nuclear site safety cases) require detailed knowledge of the site and of the risk management and operational arrangements that it has implemented and should take into account the potential impacts of climate change over the remaining lifetime of the site.
- 37 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. Since publication of the Interim Report, the Environment Agency and SEPA have taken steps alongside ONR to establish a joint expert group to inform an independent review of flood and coastal risk assessments for nuclear sites. The group will establish, on a case-by-case basis, whether there is a need to improve existing site-specific flood risk assessments and flood plans for both on- and off-site flood risks as part of the periodic safety review programme.

References

- F1 *The threat posed by tsunami to the UK. Study commissioned by Defra Flood Management* June 2005 archive.defra.gov.uk/environment/flooding/risk/tsunami.htm
- F2 *Tsunamis – Assessing the hazard for the UK and Irish coasts* Study commissioned by the Defra Flood management Division, the Health and Safety Executive and the Geological Survey of Ireland June 2006 archive.defra.gov.uk/environment/flooding/risk/tsunami.htm
- F3 www.insu.cnrs.fr/co/terre-solide/catastrophes-et-risques/seismes/sendai/sismicite-historique (in French)
- F4 *Climate Resilient Infrastructure: “Preparing for a Changing Climate”* Defra 2011 Cm8065
- F5 *Supplementary Note to Operating Authorities - Climate Change Impacts* October 2006 Defra archive.defra.gov.uk/environment/flooding/documents/policy/guidance/fcdpag/fcd3climate.pdf
- F6 *UK Climate Projections 2009* UKCP09 Defra ukclimateprojections.defra.gov.uk/content/view/1805/690/
- F7 *Joint Defra and Environment Agency Flood and Coastal Erosion Risk Management (FCERM) research and development programme* evidence.environment-agency.gov.uk/FCERM/en/Default/HomeAndLeisure/Floods/WhatWereDoing/IntoTheFuture/ScienceProgramme/ResearchAndDevelopment/FCRM.aspx

ANNEX G: SUMMARY OF FLOOD RISK TO EXISTING UK NUCLEAR INSTALLATIONS

Summary

- 1 Protection of nuclear sites from flood risks is already a well established part of ensuring safety at nuclear sites. However it is important to learn any lessons from the Fukushima event and there has been an increased interest in the flood management and protection afforded to UK licensed sites. The areas of interest include:
 - Technical basis for deriving flood heights.
 - Use of historical data.
 - Treatment of emergent data / operational feedback.
 - Impact of climate change.
 - Implications of flood defence levels lower than the design basis flood levels.
- 2 The regulatory expectation is that all sites will be capable of remaining in a safe state as a result of the threat from flooding consistent with an annual probability of exceedance, conservatively calculated of 1×10^{-4} , commonly referred to as a 1 in 10,000-year event. In addition, there should be no disproportionate increase in risk for events less likely than this.
- 3 There are a number of natural phenomena which contribute to flood hazard; still water levels, precipitation, storm surge, astronomical tides, tsunami and river flows. Climate change is likely to influence the magnitude of some of these phenomena. The local site topography, bathymetry and shoreline management arrangements all influence the nature of the hazard that is posed to the site. The dynamic and in-combination effects of the hazard also need to be taken into account in terms of the ability to damage physical protection or cause overtopping.
- 4 The safety cases vary significantly from one site to another, with varying degrees of passive or actively managed protection and the acceptability of partial flooding on the site.
- 5 For UK licensed power reactor sites, the flooding safety cases are continuously reviewed (every ten years or earlier) in detail as part of the Periodic Safety Review (PSR) process and where necessary improvements have been made. The PSR process ensures that the consideration of the magnitude of the flood hazard is reviewed on regular basis, including developments in methodologies, measured data and operational feedback. The likely slow nature of the development of climate change driven modifications to the hazard is such that there is time to develop and implement credible solutions on the periodic safety review timeframe.
- 6 These will be looked at again, consistent with Recommendation IR-10:

Recommendation IR-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.*

- 7 Establishment of a joint advisory group between the Office for Nuclear Regulation (ONR), the Environment Agency and the Scottish Environment Protection Agency (SEPA) will support this recommendation.

Introduction

- 8 This annex has been produced to summarise the current regulatory position on flood management and protection for all UK nuclear licensed sites.
- 9 Following the 2011 Tohoku event earthquake and tsunami and the publication of ONR's HM Chief Inspector of Nuclear Installations' Interim Report on the Fukushima event (Ref. [1](#)), there has been an increased interest in the flood protection of current and proposed UK nuclear licensed sites. A technical note was developed (Ref. [G1](#)) which provided a synopsis of ONR's expectations, a discussion on the technical issues prevailing in the prediction of flood risks, and the current position on each of the operating power reactor sites. This annex expands that note to cover all UK nuclear licensed sites.
- 10 The responsibility for regulating against flooding on nuclear sites is primarily ONR's. However, the environment agencies (the Environment Agency in England and Wales and SEPA in Scotland) have a broader remit on the topic of flood and coastal erosion risk management and protection of communities (see [Annex F](#)).
- 11 This report provides further information in the following areas:
- Technical basis for deriving flood heights.
 - Use of historical data.
 - Treatment of emergent data / operational feedback.
 - Impact of climate change.
 - Implications of flood defences lower than the design basis.
- 12 For a number of sites, flooding is not credible by virtue of the site topography. For others, there are no accident sequences resulting from design basis flooding events for which the off-site dose would be >0.01mSv or the on-site dose >0.1mSv.
- 13 The table below summarises those sites where the exclusions listed in paragraph 12 above do not apply.

Site	1×10^{-4} pa Flood Height (AOD) (m)	Flood Defence Heights (AOD) (m)
Barrow Dockyard	6.9	8.5 ⁽¹⁴⁾
Berkeley	10.7	9.9 ⁽¹⁰⁾
Bradwell	>5.5 ⁽¹¹⁾	5.5
Devonport Dockyard	4.3	4.3 ⁽¹⁵⁾
Dounreay	7.9	11.0
Dungeness B	7.6 8.7 ⁽⁷⁾	8.0 ⁽¹⁾
Hunterston A	5.4 ⁽¹²⁾	3.5
Hunterston B	4.8 ⁽⁸⁾	4 ⁽⁸⁾
Hinkley Point A & B	5.9 ⁽⁶⁾ 10.4 ⁽⁷⁾	8.8 (Sea wall) 12.0 (Gabion wall atop sea wall) ⁽²⁾
Hartlepool	4.2 ⁽⁴⁾	7.0 (Dunes) 5.7 (Sea wall) ⁽³⁾
Heysham 1	7.6 ⁽⁴⁾	10.7
Heysham 2	7.6 ⁽⁴⁾	9.8
LLWR	9.7	20.0
Sellafield	9.7	14.0 ⁽⁹⁾
Sizewell A	7.6 ⁽¹³⁾	10.0
Sizewell B	7.6 ⁽⁴⁾	10.0
Torness	12.8 ⁽¹⁶⁾	9.0 ⁽⁵⁾
Oldbury	9.2	10.2
Wylfa	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 run-up (tsunami effects not included as 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 Cooling Water (CW) pumphouse; however the bulk of the site is at a much higher elevation (Reactor building ground floor at +7.6m AOD).
 - (9) Platform level of lowest facility, flooding of which may have radiological consequences
 - (10) The Berkeley reactors are fully defuelled and there is no reliance on active cooling systems. This is the

platform level of the reactor building. Protection against ingress of water to the active radiological facilities is provided to a level above the 1×10^{-4} pa flood

- (11) The Bradwell reactors are fully defuelled and there is no reliance on active cooling systems Episodic flooding of some facilities is predicted as a result of the 1×10^{-4} pa event; however the potential radiological consequences are considered acceptable*
- (12) The Hunterston A reactors are fully defuelled and there is no reliance on active cooling systems Episodic flooding of some facilities is predicted as a result of the 1×10^{-4} pa event; however the potential radiological consequences are considered acceptable*
- (13) There is a potential for flooding of the CW pumphouse (floor level +7.0m AOD), which is not protected by the sand dunes. The consequences of the loss of this facility are acceptable*
- (14) Platform level of nuclear facilities*
- (15) Some overtopping from wave action is anticipated; however the volumes are tolerable*
- (16) Still water level of +3.5m AOD and 9.3m wave. Overtopping of the defences is tolerable as volumes of water can be stored and drained ahead of affecting the Reactor Building*

Scope

- 14 This annex provides a summary of the approach to flood risk management for UK nuclear Licensed Sites. Under UK law (the Health and Safety at Work etc. Act 1974 (HSAW74)) employers are responsible for ensuring the safety of their workers and the public. This responsibility is reinforced for nuclear installations by the Nuclear Installations Act 1965 as amended (NIA65), as amended. Under the relevant statutory provisions of NIA65, a site cannot have nuclear plant on it unless the user has been granted a site licence by the Health and Safety Executive (HSE). NIA65 stipulates that only a corporate body, or in other words, a legally united body that can act as one individual, such as a registered company or a public body, can hold such a licence. This licensing function is administered on HSE's behalf by ONR.
- 15 Licensed sites undertake a broad range of activities including power generation, fuel fabrication, waste treatment, defence activities isotope production and research.
- 16 There are several naval sites where nuclear-related activities occur which are under the control of the Crown (Ministry of Defence, MoD) and so are excluded from the need for licensing under NIA65. These sites operate under an Authorisation regime regulated by the Defence Nuclear Safety Regulator (DNSR), although ONR also regulates the sites through the Health and Safety at Work etc. Act 1974 and associated legislation, including the Ionising Radiations Regulations 1999 and Radiation (Emergency Preparedness and Public Information) Regulations 2001. These Authorised Sites are HM naval bases at Devonport and Clyde (which comprises the Faslane and Coulport sites) and the Vulcan Naval Reactor Test Establishment at Dounreay. ONR works jointly with DNSR at these sites where our responsibilities coincide. DNSR have issued instructions to these authorised sites following Fukushima which are similar in requirements to HM Chief Inspector of Nuclear Installation' Interim Report recommendations
- 17 The early sections of this report focus on matters which are generic to all sites. The latter sections summarise the current position on all licensed sites.

Expectations

- 18 ONR's Safety Assessment Principles (SAP), Ref. [5](#), provide the benchmark against which ONR judges the acceptability of safety justifications. The following sections summarise those SAPs which are most relevant to external flooding. There are many other aspects, including redundancy, diversity and defence in depth which are also required, which are detailed in the SAPs, but not repeated

here. In addition, as with other potential hazards, ONR will require the risks from flooding to be reduced to “as low as reasonably practicable” (ALARP).

19 Within the SAPs it is stated that:

Engineering principles: external and internal hazards	Frequency of exceedance	EHA.4
<i>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).</i>		

Fault analysis: design basis analysis	Initiating faults	FA.5
<i>The safety case should list all initiating faults that are included within the design basis analysis of the facility.</i>		

“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 1×10^{-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;*
- d) those faults leading to unmitigated consequences which do not exceed the BSL for the respective initiating fault frequency in Target 4 (paragraph 599 f.).*

Note: The risks from initiating faults in d) should be shown to be as low as reasonably practicable by application of relevant good engineering practice supported by deterministic and probabilistic analysis as appropriate.

Initiating fault frequencies should be determined on a best-estimate basis with the exception of natural hazards where a conservative approach should be adopted.”

Engineering principles: external and internal hazards	Flooding	EHA.12
<i>Nuclear facilities should withstand flooding conditions that meet the design basis event criteria.</i>		

“The area around the site should be evaluated to determine the potential for flooding due to external hazards e.g. precipitation, high tides, storm surges, barometric effects, overflowing of rivers and upstream structures, coastal erosion, seiches and tsunamis.

The design basis flood should take account, as appropriate, of the combined effects of high tide, wind effects, wave actions, duration of the flood and flow conditions.”

20 Guidance from the International Atomic Energy Agency (IAEA) in Refs [G2](#) and [G3](#) provides further information.

21 In line with the SAPs, the treatment of external hazards within the safety case is proportionate to the hazard posed by the site. There is therefore a wide range of different approaches across the different sites, commensurate with the risks posed. For many of the sites, the on- and off-site

radioactive releases from accidents which might be caused as a result of postulated flooding events are extremely small and do not warrant further detailed consideration.

Contributors to Flood Hazard

- 22 Flood hazards can arise from a single phenomenon, or from a combination thereof. The following sections identify the key contributors.

Astronomical Tides

- 23 The semidiurnal range (the difference in height between high and low waters over about a half day) varies in a two-week cycle. Approximately twice a month, around new moon and full moon when the sun, moon and Earth form a line (a condition known as syzygy) the tidal force due to the Sun reinforces that due to the moon. The tide's range is then at its maximum; this is called the spring tide.
- 24 When the moon is at first quarter or third quarter, the sun and moon are separated by 90° when viewed from the Earth, and the solar tidal force partially cancels that of the moon. At these points in the lunar cycle, the tide's range is at its minimum; this is called the neap tide. Spring tides result in high waters that are higher than average, low waters that are lower than average, "slack water" time that is shorter than average, and stronger tidal currents than average. Neaps result in less extreme tidal conditions. There is about a seven-day interval between springs and neaps.
- 25 Terms often used are Mean High Water Springs (MHWS) and Mean Low Water Springs (MLWS). The height of MHWS is the average throughout the year of two successive high waters during those periods of 24 hours when the range of the tide is at its greatest. The height of the MLWS is the average height obtained by the two successive low waters during the same period.
- 26 Highest Astronomical Tide (HAT) is the highest level, and Lowest Astronomical Tide (LAT) the lowest level that can be expected to occur under average meteorological conditions and under any combination of astronomical conditions. HAT and LAT are not extreme levels, as certain meteorological conditions can cause a higher or lower level, respectively. The level under these circumstances is known as a "storm surge" ("negative surge" in the case of level lower than LAT). HAT and LAT are determined by the analysis of predicted and actual sea levels over a number of years.
- 27 The values of astronomical tides are easily predicted and the differences between the level of HATs and the largest predicted tide are small (Ref. [G4](#)).

Storm Surge

- 28 Storm surges are provoked by meteorological phenomena, a combination of strong winds and low atmospheric pressure causes a sudden rise in coastal sea level. For a given set of environmental conditions, the magnitude of storm surges can be estimated fairly readily. A third effect due to funnelling and seiching can also contribute. A review of the previous ten years of predictions from Proudman Oceanographic Laboratories has shown that there is a clear ability to predict surge and tidal values (see www.pol.ac.uk/ntslf/model.html).

Rainfall and River Flow

- 29 Severe rainfall contributes to the flooding hazard in two key ways, through the direct build up of water on the site, which cannot be directly drained away, and secondly from the increase in flow rates for local surface drainage pathways. The increased flow in local streams and rivers may cause an increased risk of flooding from these sources including possible restrictions to access routes around sites.
- 30 These effects may be exacerbated if drainage from the site is restricted due to raised levels in drainage pathways or high tides.

Tsunami

- 31 A tsunami is an ocean wave that can travel at speeds up to 600mph (965km/hr), hundreds of miles over open sea before it hits land. A tsunami is usually caused by an earthquake, volcanic eruption or coastal or submarine landslide, which causes an initial displacement of a massive volume of water. A tsunami is a series of waves which travel outward on the ocean surface in all directions in a ripple effect. Initially, the waves are at relatively low amplitude but, as they get closer to shore, they decrease in speed and increase in height. They approach the coastline as a series of high and low water levels, typically 10-45 minutes apart. The most significant difference between tsunami waves and ordinary ocean waves is the wavelength and period, which are much much larger in the case of tsunami waves. This increased wavelength results in larger run-up values than for waves with an equivalent height generated by other means.
- 32 The prediction of tsunami effects on the UK needs to account for the large distances over which the waves must travel before impacting UK shores. The local effects of topography and bathymetry also need to be taken into account. There are a limited number of historical events which have given rise to tsunamis which have impacted the UK coastline. As a result, there is a greater degree of uncertainty associated with tsunami effects compared to other wave processes.

Climate Change

- 33 Climate change effects are many; however, for flooding, the two main contributors are an increase in sea levels and an increase in the occurrence of stormy conditions. [Annex F](#) contains a summary of the guidance available on the effects of climate change and on the approach to infrastructure adaptation. During the Periodic Safety Reviews (PSR), climate change effects over the next ten years are examined in detail using the most recently available predictive data and are generally found to be a small proportion of total flood height data. The PSR also takes a longer term view to ensure the site should be adequately protected and adapted where necessary.
- 34 Climate change effects will build up gradually, allowing the licensees adequate time to develop and deploy appropriate protective measures for any affected site. Experience to date has shown that defences can be enhanced over time to accommodate increased water levels and to provide suitable protection systems.

Historical Data

- 35 The use of historical data is key to all aspects of flood hazard prediction. The tide gauge network throughout the UK provides a regular benchmarking for tide and surge predictions (see

www.pol.ac.uk/ntslf/tidalp.html). The data collected by the Meteorological Office weather stations is used to develop extreme rainfall estimates. Within the licensees' organisations, broader knowledge from flooding incidents in the UK and further afield is taken into account in the PSRs. The nature of meteorological hazards is well understood, and the information gathered from on-going feedback is generally seen as a validation of existing practices for prediction of hazard levels rather than as a means to develop new methodologies.

Run-up

- 36 Run-up is defined as the vertical height above the still water level to which water from a specific wave will run up the face of a structure, embankment or foreshore profile. This effect is relevant for smooth slopes and sometimes rough slopes, however it is not an issue for vertical slopes. Overtopping however is relevant for all types of structures.

Overtopping

- 37 Overtopping is defined as the movement of water over the crest of a structure as a result of high still water or transient wave heights exceeding the crest height. Established methods exist for the calculation of overtopping volumes (Ref. [G4](#)).
- 38 Overtopping of the structure typically deposits a volume of water onto the site. This is typically dealt with by local drainage or by local ponding. In some cases, there are active measures to pump water from the inside of structures.
- 39 Care must also be taken to ensure that overtopping does not degrade the defence, either by lowering its height or by degrading its structural resistance potentially leading to failure.

Sea Defences

- 40 On UK nuclear licensed sites there is a variety of defence structure types as listed below.
- Natural dunes.
 - Man-made dunes.
 - Shingle berms.
 - Concrete sea walls.
 - Masonry sea walls.
 - Gabion walls.
 - Accropodes (concrete blocks used to dissipate wave energy)
- 41 These structures perform two basic functions, to protect against erosion of the land by the sea / river and secondly, to reduce the likelihood of inundation of the site. In addition, some structures provide mitigation against overtopping by waves (e.g. Gabion walls), but do not offer full protection against high still water levels due to their porosity.
- 42 Many sites also feature hard surface run-off areas behind sea walls to collect sea water which overtops the initial defences and to direct it to drains. In any significant winter storm there is

always some amount of sea water which overtops the sea defences onto the site, therefore the drainage and removal of this water is tested on a routine basis.

- 43 The failure or damage to sea defence structures or other assets involved in flood mitigation can result in flood water entering the site. The inclusion of these assets on the maintenance and test schedules provides mitigation against this risk. Engagement of the licensees with the local shoreline management groups provides a link to the broader flood and coastal risk management regime.

Methodologies

- 44 The regulatory approach is goal-setting non-prescriptive, and the guidance in the SAPs (Ref. [5](#) and Expectations section earlier) is at a relatively high level to allow appropriate approaches to be taken for individual sites. There are two key aspects to the prediction of flood hazard, the prediction of the individual components and then their treatment in combination.
- 45 There are no fixed approaches either prescribed by ONR or which have been agreed between licensees and ONR; however, there are some areas where there is general agreement.
- 46 Astronomical tide levels are well understood, and the routine predictions at site locations are complemented by recorded data at the sites gathered over time.
- 47 The effects of storm surge are based on the two components of low barometric pressure and high wind. Prediction of storm surge magnitude is a well-established science and is undertaken on a daily basis to allow the Environment Agency and SEPA to issue warnings and advice: www.environment-agency.gov.uk/homeandleisure/floods/58417.aspx and www.floodline.sepa.org.uk.
- 48 The devastating tsunami in the Indian Ocean of December 2004 prompted the commissioning of a study by the 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*" (Refs [G5](#) and [G6](#)).
- 49 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 as a result of an event similar in magnitude to that in Lisbon (1755). Simulated wave elevations on the Cornish coast are typically in the range of 1-2m, with localised amplification enhancing the elevations to approximately 4m.
- 50 The current tsunami hazard levels should be seen as extreme values for the UK, as the magnitude of the initiating event is considered to be of a maximum credible nature for the tectonic environment around the Goringe Bank. A series of sensitivity studies was performed to establish the variability in transmission towards the UK. Notwithstanding this, it has been recommended that a review of the work undertaken in 2005 and 2006 to consider emergent information on this risk be undertaken.
- 51 The calculation of a hazard level which aligns with the SAPs' expectations of a 1 in 10,000-year event is challenging, as there are clearly contributors which have significantly different probabilistic basis. This is recognised in the IAEA guide (Ref. [G3](#)) which states that "*A suitable combination of flood causing events depends on the specific characteristics of the site and involves considerable*

engineering judgement.” It later provides some suggested approaches which equate to a 1 in 10,000-year event.

- 52 Ref. [G7](#) provides some further, more detailed, guidance on the combination of events, which broadly agrees IAEA’s approach suggested in Ref. [G3](#). This work was prepared by the nuclear industry in support of early PSRs and was completed ahead of the Defra study
- 53 The approach adopted by UK licensees is based on either Ref. [G3](#) or Ref. [G7](#).
- 54 The prediction of extreme events such as a 1 in 10,000-year flood needs to take due cognisance of the considerable uncertainties. This is addressed in two ways within the SAPs. Firstly, the hazard levels should be calculated on a conservative basis and, secondly, there is a requirement to ensure that a small change in design basis parameters does not lead to a disproportionate increase in radiological consequences.

Current Position – Operating Reactor Sites

- 55 The following sections detail the current position on flooding at all existing operating power reactor sites. The information is taken from the most recent submissions provided by licensees as part of their PSRs. These reviews have been completed within the past ten years, most within the last five years. In addition, following the 2004 Indian Ocean tsunami, all licensees reviewed their protection against this hazard and provided a written response to ONR.
- 56 The broad approach to safety against flooding is based on demonstration of the following:
- A single line of protection against the 1×10^{-4} per annum (infrequent) hazard.
 - Two lines of protection against the 1×10^{-3} per annum (frequent) hazard.
- 57 The safety arguments presented are a mixture of:
- A clear demonstration that all safety-critical systems structures and components on the site are at a sufficient elevation such that flooding cannot affect them.
 - That protection against inundation is provided by robust defence structures.
 - That any water which enters the site – as envisaged by the flooding scenarios identified by the licensees – can be accommodated without affecting safety-critical systems structures and components.
- 58 The following summaries focus on the hazard levels against the 1×10^{-4} per annum infrequent event. The following should be noted:
- Water levels should be taken as still water levels unless stated to be wave heights or run-up values.
 - The values quoted are from a mixture of documents supplied during the most recent PSR and information provided by licensees as part of the response to the Fukushima accident (Ref. [G8](#)).
 - Unless stated otherwise, the levels include the effects of climate change over the remaining period to the next PSR.
- 59 The operating reactor sites have maintenance activities which include inspection and maintenance of sea defences. These are completed on a periodic basis by the licensees and reported to the Regulator. Additional inspections are also undertaken when flood warnings are received and following storms to ensure continued protection.

Dungeness B

- 60 Ref. [G9](#) provides an overview of the current safety case against external flooding, the key aspects of which are:
- The site is protected against inundation by a shingle berm, which is actively maintained by beach feeding to a level of +8.0m AOD.
 - The general site level is at +5.2m AOD.
 - The worst case 1 in 10,000-year event has been defined as a tsunami, estimated at 3m offshore, with shoreline amplification to 5.1m (run-up of 2.1m), combined with mean high water spring (+3.6m). This gives an overall elevation of +8.7m AOD.
 - The combined mean high water spring and storm surge gives an elevation of +5.4m AOD.
 - Extremes of swell and wind wave (including run-up) give an elevation of +7.6m AOD.
 - It is possible that there could be some transient flooding of the access road to the site, but this would be for a relatively short period of time.
- 61 It can be seen that for the predicted levels other than tsunami, there is no overtopping of the shingle berm. The tsunami predictions are based on work undertaken in 1995, and do not account for the most recent work in Refs [G5](#) and [G6](#). Using the most pessimistic values for the UK, which are predicted to be in Cornwall (4m), would give a worst case of +7.6m AOD, which is below the berm level.
- 62 It is noted in the safety case that extreme rainfall may cause some localised flooding on the site, but this would not compromise the availability of safety-critical equipment.
- 63 Arrangements are in place for warning of extremes of weather and tide from the Environment Agency and Meteorological Office flood forecasting centre.

Hunterston B

- 64 Ref. [G10](#) provides an overview of the current safety case against external flooding, the key aspects of which are:
- The site contains a significant change in elevation from the reactor building (+7.6m AOD) platform level to the foreshore (+2–3m AOD). This change in elevation provides the primary protection against flooding.
 - There is some physical protection along the shoreline, varying in height from +4m to +5.9m AOD.
 - The mean high water spring is defined at +1.8m AOD and the maximum astronomical tide at +2.4m AOD.
 - The worst case 1 in 10,000-year event has been estimated as +4.8m AOD.
 - The effects of tsunami at this location are predicted to be minimal. This is in line with Refs [G5](#) and [G6](#).
 - It is possible that there could be some transient flooding of the access road to the site, but this would be for a relatively short period of time.

- 65 The safety case notes that for the 1×10^{-4} infrequent event, local flooding of some areas is possible, including the cooling water pumphouse. Loss of the system functions within the pumphouse can be tolerated as a single line of system protection for all essential safety functions is available using plant and equipment in buildings located above the flood level. The topography of the site means that flood levels significantly above those predicted would be required to cause water to enter the reactor buildings.
- 66 It is noted in the safety case that extreme rainfall may cause some localised flooding on the site, but this would not compromise the availability of safety-critical equipment.
- 67 Arrangements are in place for warning of extremes of weather and tide from the Licensees own organisation, with support from SEPA as necessary.

Hinkley Point B

- 68 Ref. [G11](#) provides an overview of the current safety case against external flooding, the key aspects of which are:
- The Bristol Channel has one of the largest tidal ranges in the world, of up to 14m.
 - There is a concrete sea wall (+8.8m AOD) against the seaward frontage topped by a Gabion wall (total height +12.0m AOD).
 - The mean high water spring is defined at +5.9m AOD and the maximum combined storm surge at +8.3m AOD.
 - Taking a tsunami height (including run-up) of +4.5m and combining with MHWS gives an elevation of +10.4m AOD.
 - The worst case external flood hazard is a combined MHWS, storm surge and waves (including run-up), which give a height of +12.7m AOD. This suggests minor overtopping of the Gabion wall from wave effects.
 - The maximum still water levels are below that of the concrete sea wall, thus major inundation through the semi-porous Gabion wall is not seen as credible.
 - It is possible that there could be some transient flooding of the access road to the site, but this would be for a relatively short period of time.
- 69 The safety case notes that, for the infrequent event, local flooding of some areas is possible, including the cooling water pumphouse. Loss of the system functions within the pumphouse can be tolerated as a single line of system protection for all essential safety functions is available using plant and equipment located in buildings above the postulated flood level. The topography of the site means that a significant volume of water would need to enter the site before there would be a sufficient build up such that water could enter the reactor buildings.
- 70 It is noted in the safety case that extreme rainfall may cause some localised flooding on the site, but that this would not compromise the availability of safety-critical equipment.
- 71 There has been considerable debate over the 1607 flooding event in the Bristol Channel. This has been claimed by some researchers to be the result of a tsunami (Ref. [G12](#)), however it is considered that a more rational explanation is that of a combined storm surge and high tide (Refs [G13](#) and [G14](#)). What is certain is that there are historical records of flood levels on churches which show a peak of +7.7m AOD. Some care needs to be taken, however, in interpreting these values

directly, as sea level changes, isostatic rebound (land level changes as a result of post glacial adjustment of the crust) and long term settlement of the buildings will have had an effect. However, it is clear that even if a conservative additional height is added to account for these effects, the flood levels from an equivalent event are c.+8.5m AOD, lower than the current defences.

- 72 Arrangements are in place for warning of extremes of weather and tide from the Environment Agency and Meteorological Office flood forecasting centre.

Hartlepool

- 73 Ref. [G15](#) provides an overview of the current safety case against external flooding, the key aspects of which are:
- There is a mixture of defences for the site, comprising sand dunes on the eastern seaward side (+7.0 to +7.4m AOD) and a concrete sea wall (+5.7m AOD) against the estuary frontage.
 - The cooling water pumphouse is provided with “dam boards” (temporary flood protection applied to building openings) to provide additional protection against water ingress during extreme weather.
 - The mean high water spring is defined at +3.7m AOD and the maximum combined storm surge at +4.2m AOD. Run-up of waves is expected to result in some overtopping, but the volumes are small and easily accommodated on-site without compromising safety-essential plant.
 - Tsunami heights calculated in the first periodic safety review documents (PSR1) were conservatively estimated at 3m. The more recent work (Refs [G5](#) and [G6](#)) suggests values considerably below 1m for this location.
 - Addition of a conservative tsunami height and the maximum storm surge height results in a level below the lowest sea defence.
- 74 It is noted in the safety case that extreme rainfall may cause some localised flooding on the site, but this would not compromise the availability of safety-critical equipment.
- 75 Arrangements are in place for warning of extremes of weather and tide from the Environment Agency and Meteorological Office flood forecasting centre.

Heysham 1 and 2

- 76 Ref. [G15](#) provides an overview of the current safety case against external flooding, the key aspects of which are
- The concrete sea wall (+10.7m AOD) provides protection against the estuary frontage.
 - The cooling water pumphouses are provided with “dam boards” to provide additional protection against water ingress during extreme weather.
 - The mean high water spring is defined at +4.6m AOD and the maximum combined storm surge at +7.63m AOD. Allowing for wave run-up, it is likely that some overtopping of the wall may occur.

- Calculations of the likely volumes of water have been made and found to be readily accommodated on the site without affecting safety-critical structures systems and components.
- Tsunami heights calculated in the PSR1 documents were conservatively estimated at, at 3m. The more recent work (Refs [G5](#) and [G6](#)) suggests values considerably below 1m for this location.
- Addition of a conservative tsunami height and the mean high water springs results in a level below the lowest sea defence.

77 It is noted in the safety case that extreme rainfall may cause some localised flooding on the site, but this would not compromise the availability of safety-critical equipment.

78 Arrangements are in place for warning of extremes of weather and tide from the Environment Agency and Meteorological Office flood forecasting centre.

Oldbury

79 The power station is located on the east bank of the River Severn about 3.5 miles upstream of the first Severn crossing road bridge.

80 The risk from site flooding has been examined in detail as part of the Long Term Safety Review (LTSR) and PSR assessments. The assessments cover both externally generated flooding (i.e. that arising from extreme sea levels, wave effects, precipitation and release of off-site water storage) and internally generated flooding.

81 The key aspects of the case are:

- The site is formed from reclaimed land with sea defences built to a height of around +10.2m AOD. External to the site the land level is typically between +6m and +8m AOD and defence banks are provided to prevent overtopping by the 1 in 50-year annual probability event.
- The effects of extreme tides combined with storm surge effects yields a maximum predicted water level of +9.2m AOD for the 1×10^{-4} per annum event.
- The freeboard of 1m in the defence height is sufficient to ensure that even though the surrounding low-lying land may suffer flooding the site will not.
- The effects of spray on the site and minor overtopping have also been considered. Since there are no buildings containing nuclear safety-related plant which are liable to be soaked directly by spray the only hazard arises from accumulation of water. However, a survey of the level of the land surrounding the site shows that any spray water would drain from the site.
- The only plant fault which could arise from significant site flooding is loss of the main cooling water pumps. Two lines of reactor trip protection are provided for this fault and post trip cooling can be provided by either forced gas circulation utilising the emergency boiler feed pumps or natural circulation with back-up feed.

82 It is noted in the safety case that extreme rainfall may cause some localised flooding on the site, but this would not compromise the availability of safety-critical equipment.

83 Arrangements are in place for warning of extremes of weather and tide from the Environment Agency and Meteorological Office flood forecasting centre.

- 84 There is no specific mention of tsunami risk in the current safety justification. It is considered that the existing extreme flood levels bound the likely flood levels when tsunami is taken into consideration. It should be noted that this will be reviewed in detail as part of the recommendations from this report.

Sizewell B

- 85 The Sizewell B site is situated on a plateau at a level of +6.5m AOD. Protection of the Sizewell site relies on the broader protection of the shoreline against sea erosion and inundation. As a result, the Sizewell Shoreline Management Steering Group, through its Chairman or his nominee, provides the interface between the British Energy and Magnox Electric (who are the Sizewell A Licensees) and external authorities on matters relating to the region's coastal management.
- 86 Refs [G17](#) and [G18](#) provide an overview of the current safety case against external flooding, the key aspects of which are:
- The immediate seaward defences are +5m AOD high dunes, and behind them, a +10m AOD high man made dune structure.
 - The maximum combined storm surge at MHWS and wave run-up is estimated at +7.6m AOD
 - The tsunami risk is very low for this location (Refs [G5](#) and [G6](#)). It is clear there is sufficient margin to accommodate even the worst case UK tsunami effects when combined with MHWS.
- 87 It is noted in the safety case that extreme rainfall may cause some localised flooding on the site, but this would not compromise the availability of safety-critical equipment.
- 88 Arrangements are in place for warning of extremes of weather and tide from the Environment Agency and Meteorological Office flood forecasting centre.

Torness

- 89 Torness is located on the east coast of Scotland, a short distance from Edinburgh.
- 90 Ref. [G16](#) provides an overview of the current safety case against external flooding, the key aspects of which are:
- The primary defences for the site, comprise a series of concrete sea walls (+9 to +10m AOD).
 - The platform level for the reactor building is at +11.5m AOD.
 - The maximum combined storm surge at MHWS is +3.5m AOD.
 - The maximum wave height is predicted at 9.3m, thus giving a 10^{-4} pa hazard including wave height of +12.8m AOD.
 - Tsunami heights presented in the PSR1 documents were pessimistic, at 4m. The more recent work (Refs [G5](#) and [G6](#)) suggests values considerably below 1m for this location.
 - It is clear that overtopping of sea defences may occur for the 1×10^{-4} year event, however the overtopping volumes can be accommodated on-site and drained without causing flooding of the Reactor Buildings. The maximum predicted flood level on the site as a result of overtopping is +7.5m AOD, considerably below the platform level of +11.5m AOD. It is possible that localised flooding of the Reactor Cooling Water (RCW) pumps in the Cooling Water (CW) pumphouse

may occur, however there remain alternative means to achieve their functions which are located above the flood level..

- 91 It is noted in the safety case that extreme rainfall may cause some localised flooding on the site, but this would not compromise the availability of safety-critical equipment.
- 92 Arrangements are in place for warning of extremes of weather and tide from the Licensees own organisation, with support from SEPA as necessary.

Wylfa

- 93 Wylfa is located on the north west coast of Anglesey.
- 94 As part of the LTSR and PSR (1 and 2) assessments, the risk from external flooding was examined in detail. The main source of flood water is from the Irish Sea, and extreme precipitation, however the potential for flooding from the on-site water storage reservoir (4000m³ +) was also considered.
- 95 The majority of the safety-related structures are situated at an elevation of + 12m AOD, with only the circulating water pumphouse at a lower elevation (+10m AOD).
- 96 As part of the LTSR work, a design basis sea level of +11.4m AOD (1 x 10⁻⁴ per annum annual probability of exceedance) was calculated. During the PSR a review of this level was undertaken, which considered a broader range of measured data, and used an updated methodology which considered more correctly the probabilistic combinations of swell, storm surge and tidal effects. This resulted in a revised definition of design basis sea level of +9.4m AOD.
- 97 The basis of the case is that there are two lines of protection against a frequent flood (1 x 10⁻³ pa) and a single line of protection against a more severe design basis event (1 x 10⁻⁴ pa). The frequent flood hazard will not threaten any safety-related plant on the Wylfa site.
- 98 The infrequent flood hazard may result in water ingress into the CW pumphouse. This may result in the loss of secondary cooling to some reactor systems. Trip and shutdown functions cannot be credibly affected by external flooding. There are at least two trains of feed available, the Gas Turbine (GT) system or Electrical overlay system, Circulator Auxiliary Cooling Systems (CACs), and a demonstration that loss of Pressure Vessel Cooling Water (PVCW) can be tolerated. This ensures that there is a high confidence that the reactor can be tripped, shutdown, and adequately cooled in the event of any loss of function in the CW pumphouse.
- 99 Release of water from the on-site storage reservoir could result in a loss of grid connection due to water ingress affecting the 400kV and 132kV switch houses. This may result in tripping of the reactors; however, there would be no reduction in the availability of the claimed safety-related plant.
- 100 Extreme precipitation has been examined as a potential cause of on-site flooding. The natural gradient of the site is a benefit. A detailed review and physical inspection during the PSR of the drainage system concluded that it was fit for purpose, however it could not be ruled out that some flooding may occur in the Turbine Hall basement and the CW pumphouse as result of the 1 x 10⁻⁴ per annum event. The arguments for acceptability of this scenario are as for the external flood hazard.
- 101 Arrangements are in place for warning of extremes of weather and tide from the Environment Agency and Meteorological Office flood forecasting centre.

Current Position – Fuel Cycle Sites

- 102 The following sections detail the extant position on flooding at UK fuel cycle sites. The information is taken from the most recent submissions provided by licensees.
- 103 The safety arguments presented are a mixture of:
- a clear demonstration that all safety-critical systems structures and components on the site are at a sufficient elevation that flooding cannot affect them;
 - that protection against inundation is provided by robust defence structures; and
 - that any water which enters the site as envisaged by the flooding scenarios identified by the licensees can be accommodated without affecting safety-critical systems structures and components.
- 104 The following summaries focus on the hazard levels against the 1×10^{-4} per annum infrequent event. The following should be noted:
- Water levels should be taken as still water levels unless stated to be wave heights or run-up values.
 - The values quoted are from a mixture of documents supplied during the most recent PSR and information provided by licensees as part of the response to the Fukushima accident.
 - Unless stated otherwise, the levels include the effects of climate change over the remaining period to the next PSR.

URENCO Capenhurst and Sellafield Limited (Capenhurst)

- 105 The Capenhurst sites are located in Cheshire more than 4km from the coast. Flooding from seaward inundation can be readily dismissed as a concern. In addition, due to the local topography, flooding from local rivers and streams can be discounted as a significant hazard.
- 106 Operations at the sites require no coolant or external power supply to ensure containment of the nuclear material on the site.
- 107 There are no accident sequences resulting from design basis flooding events for which the off-site dose would be >0.01 mSv or the on-site dose >0.1 mSv

Sellafield

- 108 The Sellafield site occupies a large area housing a range of facilities fulfilling fuel reprocessing and waste storage functions. Each facility has its own individual safety case considering threats to nuclear safety and the protection measures in place. To ensure a consistency in methodology and reliability in relation to the safety of facilities ONR has agreed a set of external hazard criteria applicable to all nuclear safety structures on the Sellafield site. The agreed criteria require all plants to be subject to assessment against 1 in 10,000-year return period events arising from environmental external hazards, including flooding and seismic activity.
- 109 When considering protection against flooding, the assessments cover:

- threat from rises in sea level as a result of extreme tides in combination with wave activity and allowance for climate change;
- fluvial flooding from changes in flow of the River Calder;
- extreme rainfall and resulting overland flow of water; and
- tsunami.

110 In addition to the consideration of the potential for flooding of the site a study has been completed in relation to the potential for coastal erosion from the combined actions of tide, coastal drift and river flow. The coastal erosion study considered the likely change to coast line, river estuary silting and ingress of sea water at Sellafield and nearby Low Level Waste Repository (LLWR) sites in the medium (50-250 years) and long term (250-10000 year) time scales. The study indicates that in the medium term there is potential for the river Calder to overtop its banks at its mouth. The mouth of the river is low lying in relation to the general site level and such flooding would not threaten nuclear facilities.

111 Following the Indian Ocean event in December 2004 a reassessment of the potential effects of tsunami was completed for the Sellafield site and this was revisited in light of the Fukushima event. As a result of a combination of factors including:

- distance to any event that could generate a tsunami;
- the bathymetry of the Irish sea;
- the absence of coastal features that could magnify wave activity; and
- the general elevation of the site.

It was concluded that the Sellafield site has a very low risk of flooding as a result of tsunami activity and threat to nuclear facilities could be discounted.

112 The site elevation ranges from +9.0m AOD to +48.0m AOD, with the lowest facility with a radiological content having a ground floor level of +14.0m AOD. The predicted tide levels are as follows.

- Mean high water spring tides: +4.0m AOD.
- Extreme Tide Level 1: 10,000-year: +7.4m AOD.
- Extreme Tide Level 1: 10,000-year including wave height: +8.9m AOD.
- Extreme Tide Level 1: 10,000-year including wave height and allowance for global warming: +9.7m AOD.

The above figures do not include storm surge as combinations of extreme tides, wave height and storm surge with coincident individual probabilities of exceedance of 1×10^{-4} per annum as these contributors are not fully correlated phenomena. Modelling for a 1 in 50-year storm surge indicates that a 2m increase in sea level is probable and, if such an increase was included, the maximum sea level with extreme tide could reach +10.9m AOD.

113 In past years the channel of the River Calder has been straightened for a design flow of $310\text{m}^3/\text{s}$ and the estimated 1 in 10,000-year flow in the river is estimated as $326\text{m}^3/\text{s}$. Although some flooding is indicated, the topography of the site ensures that the flooding would be confined to the east bank affecting the decommissioning Calder Hall site, but that there would be no flooding of safety-related facilities.

- 114 Extreme rainfall intensities have been modelled for 1 in 1000 and 1 in 10,000-year events with the inclusion of allowance for global warming. The modelling indicates surcharging of surface water drainage systems and local flooding of the site at low-lying car park and hard-standing areas.

Springfields

- 115 The Springfields site is located in Lancashire more than 10km from the coast. Flooding from seaward inundation can be readily dismissed as a concern. There is a small stream which passes through the site, however this does not have the potential to inundate safety-critical structures.
- 116 Operations at the site require no coolant or external power supply to ensure containment of the nuclear material on the site.
- 117 There are no accident sequences resulting from design basis flooding events for which the off-site dose would be >0.01 mSv or the on-site dose >0.1 mSv

Current Position – Decommissioning Sites

- 118 In line with the SAPs, the treatment of external hazards within the safety case is proportionate to the hazard posed by the site. There is, therefore, a wide range of different approaches across the different decommissioning sites, commensurate with the risks posed. For many of the sites, the on- and off-site radioactive releases that may result from the direct or indirect effects of the postulated flooding events are extremely small and do not warrant further detailed consideration.

Berkeley

- 119 The Berkeley site now comprises the former power station and the Berkeley Centre (formerly the Berkeley Nuclear Laboratories). The Berkeley reactors are shut down and empty of fuel as is the cooling pond. The bulk of the radiological inventory is contained within the Active Effluent Treatment Plant (AETP) and the Active Waste Vaults (AWV). There is currently only a very small proportion of the radiological inventory on-site compared to when the site was fully operational. The facilities are in a passively safe state and do not have safety-related dependence upon on- or off-site services.
- 120 Platform level is at +9.9m AOD, with the lowest foreshore level at the power station and centre sites set at +9.7m AOD. The predicted 1×10^{-4} per annum flood is predicted to have a height of about +10.7m AOD. This means, therefore, that a number of facilities will be at risk of flooding. (Ref. [G19](#))
- 121 Additional protection from stop logs and flood barriers has been provided to limit entry of water into those facilities containing nuclear material that has the potential for mobility once flooded. For other facilities, it has been shown that the levels of contamination potentially released as the flood waters recede are trivial.
- 122 The effects of tsunami at this location are seen to be minimal and within the bounds of the extreme flood levels previously described.

Bradwell

- 123 The Bradwell reactors are shut down and empty of fuel, as is the cooling pond. The bulk of the radiological inventory is contained within the Active Waste Vaults. It is estimated that there is currently only 0.2% of the radiological inventory on-site compared to when the site was fully operational (Ref. [G20](#)).
- 124 As part of the post-defuelling safety case, the risks from external flooding were examined. The site elevation adjacent to safety-related buildings is at +5.5m AOD. The sea wall is at a height of between +4.5m and +5.0m AOD.
- 125 The flood risk assessment makes the following key assumptions:
- During the 1 in 200-year event, there will be minor inundation of the site, but no entry of water into safety-related structures.
 - During the 1 in 1000-year event, there would be more significant flooding onto the site, possibly to a height of +5.13m AOD during the few hours either side of high tide. There would be no flooding of safety-related structures.
 - The 1 in 10,000-year event may well result in rather more significant effects on-site, including loss of electrical supplies and entry of water into some structures. Within the reactor building the effects would be minimal from a radiological perspective.
- 126 The flooding safety case claims that there would be limited ingress into the active vaults as a result of their design. Furthermore, should flooding of the active vaults occur, with the generation of hydrogen which could lead to a fire, the subsequent off-site release would be below 5mSv. This is within the range of the Basic Safety Objectives (BSO) in ONR's SAPs (Target 8 applied to single accident class).
- 127 Tsunami risk in this location is small (Refs [G5](#) and [G6](#)), and bounded by storm surge.

Chapelcross

- 128 The Chapelcross site is over 4km from the coast and 2km from the River Annan. Sea flooding and tsunami effects can be readily dismissed. There is sufficient elevation between the River Annan and the site that flooding of the site from this source is not credible. Equally, given the low magnitude of tsunami predicted at this location and the site elevation, flooding from this source is not credible. There may be some local flooding effects on-site from minor watercourses.

Dounreay

- 129 There are no operational reactors on the site, nor holdings of heat-generating materials that require active cooling. The facilities are designed to migrate to a passively safe state and do not have safety-related dependence upon on- or off-site services.
- There is no man-made flood protection explicitly provided to protect the Dounreay site. The 1 in 10,000-year sea and storm surge height is predicted to be +7.9m AOD. The height of the foreshore cliffs is +11.0m AOD and the elevations of site facilities are such that there is not a concern over seaward flooding affecting the safety of the site.
 - The risk from tsunami as a result of the re-activation of the Storegga slides in Norway was discussed in Refs [G5](#) and [G6](#). It is known that these slides have produced tsunamis in the

geological past which have affected north east Scotland. However, the geological model suggests that another glaciation (on timescales of about 100,000 years) is needed to re-establish the conditions required for a similar failure at that location.

Low Level Waste Repository

130 The Low level Waste Repository (LLWR) site is approximately 2km long by half a kilometre wide and is located adjacent to the bank of a tidal estuary near Drigg in west Cumbria. Site elevation varies between +20.0m AOD at the north-east and west end to approximately +5.0m AOD at the south-eastern boundary close to the river estuary. Although close to the coast the site does not have a coastal boundary and on the coastal elevation is protected by continuous well established sand dunes reaching a level of +20m AOD. The elevation of the various storage and disposal facilities ranges from +12.5m to +20m AOD.

131 The following summarises the hazards levels at the site:

- Mean high water spring tide: +3.4m AOD.
- Extreme Tide Level: 1 in 10,000-year: +7.4m AOD.
- Extreme Tide Level: 1 in 10000-year including wave height: +8.9m AOD.
- Extreme Tide Level: 1 in 10000-year including wave height and allowance for climate change induced sea level: +9.7m AOD.

Modelling for a 1 in 50-year storm surge indicates that a 2m increase in sea level is probable and if such an increase was included, the maximum sea level with extreme tide could reach +10.9m AOD.

132 Tsunami risk at LLWR is extremely low as a result of its distance from driving mechanisms. Given the clear margin available between the maximum predicted flood heights and the dune protection, flooding impacts are considered to be minimal.

Dungeness A

133 The Dungeness A reactors are shutdown and partially defuelled. Full defuelling is expected to be completed by the end of 2012.

134 Protection of the site against ingress of sea water is via the same mechanisms as for Dungeness B, and is repeated below.

- The site is protected against inundation by a shingle berm, which is actively maintained by beach feeding to a level of +8.0m AOD.
- The general site level is at +5.5m AOD.
- The worst case 1 in 10,000-year event has been defined as a tsunami, estimated at 3m, with shoreline amplification to 5.1m (run-up of 2.1m), combined with mean high water spring (+3.6m). This gives an overall elevation of +8.7m AOD.
- The combined mean high water spring and storm surge give an elevation of +5.4m AOD.
- Extremes of swell and wind wave (including run-up) gives an elevation of +7.2m AOD.
- It is possible that there could be some transient flooding of the access road to the site, but that this would be for a relatively short period of time.

- 135 It can be seen that for the predicted levels, other than tsunami, there is no overtopping of the shingle berm. The tsunami predictions are based on work undertaken in 1995 and are not cognisant of the most recent work in Refs [G5](#) and [G6](#). Using the most pessimistic values for the UK, which are sited in Cornwall, would give a worst case of +7.6m AOD, which is below the berm level.
- 136 It is noted in the safety case that extreme rainfall may cause some localised flooding on the site, but this would not compromise the availability of safety-critical equipment.
- 137 Arrangements are in place for warning of extremes of weather and tide from the Environment Agency and Meteorological Office flood forecasting centre.

GE Healthcare Limited

- 138 GE Healthcare Limited (GEHC) has three nuclear licensed sites in the UK; The Grove Centre at Amersham; The Maynard Centre at Cardiff and a building at Harwell. All of these facilities have extremely small amounts of nuclear material and none of these facilities requires off-site emergency plans.
- 139 The sites at Harwell and Amersham are not at risk from flooding from any source. The Cardiff site may suffer some degree of flooding on a relatively frequent (1 in 100-year event); however, the containment of the nuclear material is resilient to such events.
- 140 For all three sites, there are no accident sequences resulting from design basis flooding events for which the off-site dose would be >0.01 mSv or the on-site dose >0.1 mSv.

Harwell

- 141 Harwell site is located in Oxfordshire, over 50km from the coast. Flooding from seaward inundation can be readily dismissed as a concern. There are no streams or rivers which have the potential to inundate the site
- 142 Licensed facilities on this site are undergoing decommissioning and care and maintenance activities. The research reactors have been defuelled so do not have the potential to lead to a long-term severe accident.
- 143 There are no accident sequences resulting from design basis flooding events for which the off-site dose would be >0.01 mSv or the on-site dose >0.1 mSv.

Hinkley Point A

- 144 The Hinkley Point A reactors are shut down and empty of fuel, as is the cooling pond. The key features of the flooding safety case are:
- The Bristol Channel has one of the largest tidal ranges in the world, of up to 14m.
 - There is a concrete sea wall (+8.8m AOD) against the seaward frontage topped by a Gabion wall (total height +12.0m AOD).
 - The ground floor level of all safety-related buildings is at a minimum of +11.2m AOD
 - The mean high water spring is defined at +5.9m AOD and the maximum combined storm surge at +8.3m AOD.

- Taking a tsunami height (including run-up) of 4.5m and combining with MHWS gives an elevation of 10.4m.
- The worst case external flood hazard is a combined MHWS, storm surge and waves (including run-up), which give a height of 12.7m. This suggests minor overtopping of the Gabion wall from wave effects.
- The maximum still water levels are below that of the concrete sea wall, thus major inundation through the semi-porous Gabion wall is not seen as credible.
- It is possible that there could be some transient flooding of the access road to the site, but this would be for a relatively short period of time.

Hunterston A

- 145 The Hunterston A reactors are shut down and empty of fuel, as is the cooling pond. The bulk of the radiological inventory is contained within the Active Waste Vaults. There is currently less than 1% of the radiological inventory on-site compared to when the site was fully operational. The reactors at Hunterston A are of a particular design which means that they are suspended 15m above ground level. The focus on the flooding safety case is therefore on the waste treatment and storage facilities.
- 146 The foreshore varies in elevation from +3.5m AOD to +12.0m AOD, with platform levels at c.+4.5m AOD. The 1×10^{-4} per annum flood is predicted to potentially flood the site to a depth of 0.4m.
- 147 The effects on the solid active waste bunkers, active effluent treatment plant and on the intermediate level waste store of this level of flooding have been shown to be negligible.

Imperial College Consort Reactor

- 148 The Ascot site is located in Surrey, over 50km from the coast. Flooding from seaward inundation can be readily dismissed as a concern. There are no streams or rivers which have the potential to inundate the site.
- 149 Potential hazards from the licensed facilities on this site are limited to on-site. The site is at the early stages of a decommissioning programme.
- 150 There are no accident sequences resulting from design basis flooding events for which the off-site dose would be >0.01 mSv or the on-site dose >0.1 mSv.

Metals Recycling Facility Lillyhall

- 151 The Lillyhall site is located more than 3km from the coast. Flooding from seaward inundation can be readily dismissed as a concern. In addition, due to the local topography, flooding from local rivers and streams can be discounted as a significant hazard.
- 152 The site handles small quantities of low activity material in batch-wise operations and requires no coolant or external power supply to ensure containment of the nuclear material on the site.
- 153 There are no accident sequences resulting from design basis flooding events for which the off-site dose would be >0.01 mSv or the on-site dose >0.1 mSv

Sizewell A

- 154 The Sizewell A reactors are shutdown and partially defuelled. Full defuelling is expected to be completed by the end of 2012. The requirements on cooling for the reactors are extremely small, and tolerant to extended periods without active cooling.
- 155 The Sizewell A site is situated on a plateau at a level of +9.45m AOD. Protection of the Sizewell site relies on the broader protection of the shoreline against sea erosion and inundation. As a result, the Sizewell Shoreline Management Steering Group, through its Chairman or his nominee, provides the interface between the companies and external authorities on matters relating to the region's coastal management.
- 156 The key aspects of the current safety case against external flooding are:
- The natural elevation of the site precludes flooding of the reactor buildings.
 - The immediate seaward defences along the Sizewell B frontage are +5m AOD high dunes, and behind them, a +10.0m AOD high man-made dune structure.
 - The maximum combined storm surge at MHWS and wave run-up is estimated at +7.6m AOD
 - The tsunami risk is very low. It is clear there is sufficient margin to accommodate the worst-case UK tsunami effects when combined with MHWS.
 - Some localised flooding of the CW pumphouse – which is at a lower elevation (protection wall at +7.0m) – may occur. However, this is deemed as low risk in terms of occurrence. The loss of cooling is tolerable for several days, and the installed tertiary feed system can be readily augmented through the use of mobile pumps.
- 157 It is noted in the safety case that extreme rainfall may cause some localised flooding on the site, but this would not compromise the availability of safety-critical equipment.
- 158 Arrangements are in place for warning of extremes of weather and tide from the Environment Agency and Meteorological Office flood forecasting centre.

Trawsfynydd

- 159 The Trawsfynydd reactors, located in north Wales, are shut down and empty of fuel, as is the cooling pond. The bulk of the radiological inventory is contained within the Active Waste Vaults. The radiological inventory on-site compared to when the site was fully operational is less than 1%.
- 160 The location of Trawsfynydd a significant distance inland means that sea flooding and tsunami effects can be dismissed readily. Failure of the dam supporting Trawsfynydd Lake cannot result in flood waters entering the site. The only credible source of flooding on-site is from extreme rainfall or snow. Any effects will be transient, and cannot give rise to radiological releases that would lead to radiation doses greater than the BSO.

Winfrith

- 161 The Winfrith site is located in Dorset, about 6km from the coast. Flooding from seaward inundation can be reasonably dismissed as a concern. To the north of the site lies the River Frome. There is

sufficient elevation between the river and the site that flooding of the site from the river is not credible. Some local standing water following periods of heavy rain is anticipated on the site.

- 162 Licensed facilities on this site are undergoing decommissioning and care and maintenance activities. The research reactors have been defuelled so do not have the potential to lead to a long-term severe accident.
- 163 There are no accident sequences resulting from design basis flooding events for which the off-site dose would be >0.01 mSv or the on-site dose >0.1 mSv.

Current Position – Defence Sites

- 164 As noted earlier, this report is concerned with nuclear licensed sites, and there is no further consideration given to sites authorised by DNSR. This includes part of HM naval base at Devonport, HM Naval Base Clyde (which comprises the Faslane and Coulport sites), and the Vulcan Naval Reactor Test Establishment adjacent to Dounreay.

Atomic Weapons Establishment Aldermaston and Burghfield

- 165 The Atomic Weapons Establishment (AWE) provides and maintains the warheads for the country's nuclear deterrent, Trident. Trident is a submarine-launched, inter-continental ballistic nuclear missile weapons system, carried by Royal Navy Vanguard-class submarines. AWE manufactures and sustains the warheads for the Trident system.
- 166 The Aldermaston-sites are located in Berkshire, more than 20km from the coast. Flooding from seaward inundation can be readily dismissed as a concern.
- 167 The sites are at elevations of +100m and +45m AOD respectively. The only flood risk to these sites is from rapid rainfall events and associated run-off from local catchments. Local build-up of water on the sites from these effects is possible. In 2007, flooding on the Burghfield site led to extensive re-appraisal of both sites and the installation of flood protection measures on the Burghfield site. All new facilities being constructed on the sites take due account of the flood risk.

Barrow-in-Furness Dockyard

- 168 The Barrow complex includes the Devonshire Dock Hall, a large indoor facility that was used to build the Vanguard Class submarines and where currently the Astute Class submarines are being constructed. Within the complex, a ship lift facility is utilised to lower vessels into the water without reliance on tidal conditions. As well as construction, the commissioning and testing of submarines take place within the facility
- 169 The current safety case against external flooding can be summarised as follows:
- The worst case 1 in 10,000-year combined flood height, based on HAT combined with storm surge and including allowance for climate change, is +6.9m AOD.
 - The effect of tsunami at this location is predicted to be minimal (Refs [G5](#) and [G6](#)).
 - Town flood defences protect against tide levels of +5.0m AOD.

- The site contains a significant change in elevation from the town sea flood defences, with the floor level of the build facilities at +8.5m AOD. The entry of flood waters into the safety-critical facilities is prevented by means of the site topography.

- 170 Once launched the submarine is in its natural environment and therefore there is no compromise to the safety-critical equipment. There is no operation of the reactor in the build facilities, therefore no demand for heat removal. Reactor commissioning takes place following launch, at which point all submarine safety-critical equipment is operational and therefore not dependent on the availability of shore systems.
- 171 The safety case notes that for the 1×10^{-4} per annum event local flooding of some areas is possible on the site but this would not compromise the availability of safety-critical systems. It is also noted that extreme rainfall may cause some localised flooding on the site, but this would not compromise the availability of safety-critical equipment.

Devonport Dockyard

- 172 The Devonport dockyard site is located on the Hamoaze an estuarine stretch of the tidal River Tamar, between the River Lynher and Plymouth Sound in Plymouth.
- 173 The cope level (top of sea wall facing the Hamoaze) is at +4.3m AOD.
- 174 The 1×10^{-4} per annum combined astronomical (HAT) and storm surge height is estimated at +4.3m AOD. It is likely that some wave overtopping into the dockyard will occur, however the volumes will be tolerable.
- 175 The combined HAT and tsunami is estimated at +3.9m AOD. The tsunami risk is mitigated as a result of the local geography.
- 176 Flooding from water courses is not applicable to the Devonport Dockyard site as there are no catchment run-off channels adjacent to the facilities.

Rolls Royce Derby (Neptune and Fuel Production Plant)

- 177 The Rolls Royce Derby site is located in Derbyshire more than 50km from the coast. Flooding from seaward inundation can be readily dismissed as a concern. The site is located on the floodplain of the River Derwent.
- 178 Potential causes of flooding on the site are from the River Derwent overtopping site defences, failure of dams on the River Derwent upstream of the site and heavy rainfall. The elevation of the site is between +41.8 and +42.6m AOD.
- 179 The latest flooding assessments indicate that maximum water levels on-site from a 1×10^{-4} per annum flooding event could reach +43.2m AOD due to overtopping of the river defence. Arrangements are in place for the Environment Agency and Severn Trent to supply the site with early warning of extreme flood events. In the event of such a warning being received, vulnerable material can be moved to safe locations.
- 180 It is noted in the safety case that extreme rainfall may cause some localised flooding on the site, but this would not compromise the availability of safety-critical equipment.

Rosyth Royal Dockyard

- 181 Rosyth Royal Dockyard was used to support the refitting and maintenance of nuclear powered submarines until such work was transferred to Devonport. The nuclear licensed site is a relatively small part of the overall dockyard and most of the nuclear-related facilities have now been decommissioned and the hazard removed. None of the decommissioned submarines at present berthed at Rosyth contain nuclear fuel. Relatively small quantities of radioactive wastes are currently stored on the site. The nuclear facility is not dependent on external services or internal systems to ensure its safety.
- 182 The site is situated on level reclaimed land at a nominal height of +4.7m AOD, which is above the predicted 1×10^{-4} per annum flood height for tidal and storm surge effects. There are no additional engineered defences against inundation caused by extreme high water levels.
- 183 The key features of the defences against extreme flooding are:
- The ground floor level of the nuclear facility is +5.2m AOD.
 - The site level at the seafront is +4.7m AOD.
 - The 10^{-4} per annum flood height is +4.4m AOD based on the combined effect of extreme high tide coincident with a storm surge.

Operational Experience

- 184 At Oldbury, local flooding of the land adjacent to the site caused temporary suspension of normal access when a small local river flooded the land and road onto the site. Access was restored for site personnel using high ground clearance vehicles. The river flooding was caused by high rainfall and by local blockages of bridges and drains allowing water levels to increase. The power station-site was temporarily islanded and no disruption was caused to power generation. There were no effects of safety-related systems structures or components.
- 185 Following flood warning predictions for the east coast of England in 2008, all of the sites on the east coast took precautionary measures. At all sites, the sea water defences were inspected. In addition, at Sizewell B, a number of diesel-driven pumps normally held off-site were sent to site to assist with flood water removal should they prove necessary. These pumps were not needed. At Hartlepool the local enhancement to sea defences consisting of dam boards and sand bags applied to site and building access points, was deployed. These additional defences were not required in this event.
- 186 The Burghfield site suffered some flash flooding following rainwater run-off in 2000 and 2007. Remedial works to improve the on- and off-site drainage have since been implemented.
- 187 The major flooding in Cumbria in 2009 did not directly affect the Sellafield or LLWR sites; however, there were challenges to the local supporting infrastructure.
- 188 A flooding event at the Blayais site in France, in 1999, caused by a combination of high tide, storm surge, wind-driven waves and river flooding, created significant difficulties. This event has been well documented by the French Regulator and IAEA, and the learning from it regarding combining events with the same or similar initiating weather conditions has been well disseminated within the nuclear industry in the UK. The lessons learnt are incorporated into all the latest PSR assessments and in the latest IAEA guidance.

- 189 The event caused significant flooding of the adjacent land to the site, requiring the use of army high ground clearance vehicles to provide access for personnel and equipment. In addition, there was flooding to site-based service trenches and underground ducts, allowing flood water to enter buildings which were notionally protected against such flooding.
- 190 In June 2011, flood waters from the Missouri river surrounded the Fort Calhoun plant and remained at a significant level until early September. At the time, the plant was defuelled awaiting a new fuel load. The partial collapse of a temporary berm meant that some facilities were flooded, and as a result, the on-site diesel generators were used to provide essential power to the site until the berm had been reinstated.

Future Activities

- 191 The PSR process will continue on the timeframes established with each licensee and continue to demand that the external hazards safety cases are up to date, and reflect best practice and modern standards. This will reflect the latest guidance on climate change effects issued from UK Climate Impacts Programme (UKCIP), IAEA and other government guidance available at the time.
- 192 Recommendation IR-10 requires that:

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.

Establishment of a joint advisory group between ONR and the Environment Agency and SEPA will support this recommendation.

Conclusions

- 193 A high-level review of the claims made in the safety submissions for **all** licensed sites in the UK has been undertaken. It has concluded the following:
- The 1×10^{-4} flood hazard estimates have been reviewed as part of the PSR process.
 - The effects on safety-critical structures, systems and components have been assessed, and found to be acceptable.
 - The safety justifications accept that, in some cases, water will enter the site, but that the effects are tolerable.
 - For some sites the hazard is extremely low, and further detailed justification not warranted.
 - The effects of climate change and the potential for tsunami have been taken into account in the work.
- 194 The methodologies used appear to be in line with current guidance and with ONR's SAPs.
- 195 Notwithstanding the above, this report includes a recommendation that licensees review their flooding studies in the light of the Japanese experience to confirm design bases and whether further enhancements can be made. This is in line with regulatory expectations for continuous

improvement and learning from experience. This work will be scrutinised by ONR supported by colleagues from the environment agencies.

References

- G1 *Japanese earthquake and tsunami: Implications for the UK Nuclear Industry* Technical Note Flooding ONR Report ONR-FR-TN-11-002 Revision 0 5 June 2011
- G2 *Meteorological Events in Site Evaluation for Nuclear Power Plants Safety Guide* Safety Standards IAEA Safety Guide Series No. NS-G-3.4
- G3 *Flood Hazard for Nuclear Power Plants on Coastal and River Sites Safety Guide* IAEA Safety Guide Safety Standards Series No. NS-G-3.5
- G4 EurOtop “Wave overtopping of Sea Defences and Related Structures: assessment Manual” January 2007 www.overtopping-manual.com/eurotop.pdf
- G5 *The threat posed by tsunami to the UK* Defra 2005 archive.defra.gov.uk/environment/flooding/documents/risk/tsunami05.pdf
- G6 *Tsunamis - Assessing the Hazard for the UK and Irish Coasts* Defra 2006 archive.defra.gov.uk/environment/flooding/documents/risk/tsunami06.pdf
- G7 *Mouchel Report “Methodology for the Assessment of Flooding Hazard from Extreme Sea Levels”* January 1995 An IMC Report
- G8 *British Energy summary spreadsheet of flood and seismic magnitudes at operational sites*
- G9 *Dungeness B Periodic Safety Review 2 Report 4.05 Periodic Safety Review Internal and External Hazards Appendix 12 External Flooding* British Energy document DNB/PSR2/MR/4.05 App012 Rev 00 March 2007
- G10 *Hunterston B Periodic Safety Review 2 Report 4.05 Periodic Safety Review Internal and External Hazards Appendix 12 External Flooding* British Energy document HNB/PSR2/MR/4.05 App012 Rev 00 March 2006
- G11 *Hinkley Point B Periodic Safety Review 2 Report 4.05 Periodic Safety Review Internal and External Hazards Appendix 12 External Flooding* British Energy document HINB/PSR2/MR/4.05 App012 Rev 00 March 2006
- G12 *Was the AD 1607 coastal flooding event in the Severn Estuary and Bristol Channel (UK) due to a tsunami?* Bryant and Haslet Archaeology in the Severn Estuary, 13, 163-167 2002
- G13 *Horsburgh, K.J. and Horritt, M. (2006), The Bristol Channel floods of 1607 - reconstruction and analysis.* Weather, 61(10), 272-277
- G14 [1607 Bristol Channel Floods: 400-Year Retrospective](#) RMS January 2007
- G15 *Hartlepool and Heysham 1 Power Stations Periodic Safety Review 2 Main Report 5.12 External Flooding* British Energy document HRA/R/PSR2/MR/5.12 Rev 001 December 2007
- G16 *Heysham 2 and Torness Power Stations Periodic Safety Review 2 Main Report 5.12 External Flooding* British Energy document HYB/PSR2/MR/R & TOR/PSR2/MR/R5.12 Rev 001 November 2008
- G17 *Sizewell B Station Safety Report - General Design Aspects Hazard Protection Implementation.* SXB-IP-772001-594 Chapter 3

- G18 *Sizewell B Periodic Safety Review Safety Analysis Based Review: 2.5 Hazards Developments. SXB-IP-82013 rev 002.*
- G19 *Consolidated Safety Case for Berkeley Site Radioactive Waste Facilities (2010). Berkeley Site NP/SC 5097 Rev 1 BNLS/DPAF/2/1768 Issue 1 Rev 1 May 2011*
- G20 *Bradwell Site - Bradwell Re-Baselined (Post-Defuelling) Safety case External Hazards Assessment. Document No BRAD/DEC/REP/058 Issue 3 July 2008*

ANNEX H: EUROPEAN COUNCIL STRESS TESTS

(Reproduced verbatim from the ENSREG Specifications)

EU “Stress Tests” Specifications

Introduction

Considering the accident at the Fukushima nuclear power plant in Japan, the European Council of March 24th and 25th declared that “the safety of all EU nuclear plants should be reviewed, on the basis of a comprehensive and transparent risk assessment (“stress tests”); the European Nuclear Safety Regulatory Group (ENSREG) and the Commission are invited to develop as soon as possible the scope and modalities of these tests in a coordinated framework in the light of the lessons learned from the accident in Japan and with the full involvement of Member States, making full use of available expertise (notably from the Western European Nuclear Regulators Association); the assessments will be conducted by independent national authorities and through peer review; their outcome and any necessary subsequent measures that will be taken should be shared with the Commission and within ENSREG and should be made public; the European Council will assess initial findings by the end of 2011, on the basis of a report from the Commission”.

On the basis of the proposals made by WENRA at their plenary meeting on the 12-13 of May, the European Commission and ENSREG members decided to agree upon “an initial independent regulatory technical definition of a “stress test” and how it should be applied to nuclear facilities across Europe”. This is the purpose of this document.

Definition of the “stress tests”

For now we define a “stress test” as a targeted reassessment of the safety margins of nuclear power plants in the light of the events which occurred at Fukushima: extreme natural events challenging the plant safety functions and leading to a severe accident.

This reassessment will consist:

- In an evaluation of the response of a nuclear power plant when facing a set of extreme situations envisaged under the following section “technical scope” and
- In a verification of the preventive and mitigative measures chosen following a defence-in-depth logic: initiating events, consequential loss of safety functions, severe accident management.

In these extreme situations, sequential loss of the lines of defence is assumed, in a deterministic approach, irrespective of the probability of this loss. In particular, it has to be kept in mind that loss of safety functions and severe accident situations can occur only when several design provisions have failed. In addition, measures to manage these situations will be supposed to be progressively defeated.

For a given plant, the reassessment will report on the response of the plant and on the effectiveness of the preventive measures, noting any potential weak point and cliff-edge effect, for each of the considered extreme situations. A cliff-edge effect could be, for instance, exceeding a point where significant flooding of plant area starts after water overtopping a protection dike or exhaustion of the capacity of the batteries in the event of a station blackout. This is to evaluate the robustness of the defence-in-depth approach, the

adequacy of current accident management measures and to identify the potential for safety improvements, both technical and organisational (such as procedures, human resources, emergency response organisation or use of external resources).

By their nature, the stress tests will tend to focus on measures that could be taken after a postulated loss of the safety systems that are installed to provide protection against accidents considered in the design. Adequate performance of those systems has been assessed in connection with plant licensing. Assumptions concerning their performance are re-assessed in the stress tests and they should be shown as provisions in place. It is recognised that all measures taken to protect reactor core or spent fuel integrity or to protect the reactor containment integrity constitute an essential part of the defence-in-depth, as it is always better to prevent accidents from happening than to deal with the consequences of an occurred accident.

Process to perform the “stress tests” and their dissemination

The licensees have the prime responsibility for safety. Hence, it is up to the licensees to perform the reassessments, and to the regulatory bodies to independently review them.

The timeframe is as follows:

The national regulator will initiate the process at the latest on June 1 by sending requirements to the licensees.

	Progress report	Final report
Licensee report	August 15	October 31
National report	September 15	December 31

- The final national reports will be subjected to the peer review process described below.
- The European Commission, with the support of ENSREG, will present a progress report to the EU Council for the meeting scheduled on 9th December 2011 and a consolidated report to the EU Council for the meeting scheduled for June 2012.

Due to the timeframe of the stress test process, some of the engineering studies supporting the licensees' assessment may not be available for scenarios not included in the current design. In such cases engineering judgment is used.

During the regulatory reviews, interactions between European regulators will be necessary and could be managed through ENSREG. Regulatory reviews should be peer reviewed by other regulators. ENSREG will put at the disposal of all peer reviews the expertise necessary to ensure consistency of peer reviews across the EU and its neighbours.

Peer review process

In order to enhance credibility and accountability of the process the EU Council asked that the national reports should be subjected to a peer review process. The main purpose of the national reports will be to draw conclusions from the licensees' assessment using the agreed methodology. The peer teams will review the fourteen national reports of Member States that presently operate nuclear power plants and of those neighbouring countries that accept to be part of the process.

- **Team composition.** ENSREG and the Commission shall agree on team composition. The team should be kept to a working size of seven people, one of whom should act as a chairperson and a second one as rapporteur. Two members of each team will be permanent members with the task to ensure overall consistency. The Commission will be part of the team. Members of the team whose national facilities are under review will not be part of that specific review. The country subject to review has to agree on the team composition. The team may be extended to experts from third countries.
- **Methodology.** In order to guarantee the rigor and the objectivity of any peer review, the national regulator under review should give the peer review team access to all necessary information, subject to the required security clearance procedures, staff and facilities to enable the team, within the limited time available.
- **Timing.** Reviews should start immediately when final national reports become available. The peer reviews shall be completed by the end of April 2012.

Transparency

National regulatory authorities shall be guided by the "principles for openness and transparency" as adopted by ENSREG in February 2011. These principles shall also apply to the EU "stress tests".

The reports should be made available to the public in accordance with national legislation and international obligations, provided that this does not jeopardize other interests such as, inter alia, security, recognized in national legislation or international obligations.

The peer will review the conclusions of each national report and its compliance with the methodology agreed. Results of peer reviews will be made public.

Results of the reviews should be discussed both in national and European public seminars, to which other stakeholders (from non nuclear field, from non governmental organizations, etc) would be invited.

Full transparency but also an opportunity for public involvement will contribute to the EU "stress tests" being acknowledged by European citizens.

Technical scope of the "stress tests"

The existing safety analysis for nuclear power plants in European countries covers a large variety of situations. The technical scope of the stress tests has been defined considering the issues that have been highlighted by the events that occurred at Fukushima, including combination of initiating events and failures. The focus will be placed on the following issues:

a) Initiating events

- Earthquake
- Flooding

b) Consequence of loss of safety functions from any initiating event conceivable at the plant site

- Loss of electrical power, including station black out (SBO)
- Loss of the ultimate heat sink (UHS)
- Combination of both

c) Severe accident management issues

- Means to protect from and to manage loss of core cooling function
- Means to protect from and to manage loss of cooling function in the fuel storage pool
- Means to protect from and to manage loss of containment integrity

b) and c) are not limited to earthquake and tsunami as in Fukushima: flooding will be included regardless of its origin. Furthermore, bad weather conditions will be added.

Furthermore, the assessment of consequences of loss of safety functions is relevant also if the situation is provoked by indirect initiating events, for instance large disturbance from the electrical power grid impacting AC power distribution systems or forest fire, airplane crash.

The review of the severe accident management issues focuses on the licensee's provisions but it may also comprise relevant planned off-site support for maintaining the safety functions of the plant. Although the experience feedback from the Fukushima accident may include the emergency preparedness measures managed by the relevant off-site services for public protection (fire-fighters, police, health services....), this topic is out of the scope of these stress tests.

The next sections of this document set out:

- General information required from the licensees;
- Issues to be considered by the licensees for each considered extreme situation.

General aspects

Format of the report

The licensee shall provide one document for each site, even if there are several units on the same site. Sites where all NPPs are definitively shutdown but where spent fuel storages are still in operation shall also be considered.

In a first part, the site characteristics shall be briefly described:

- location (sea, river);
- number of units;
- license holder

The main characteristics of each unit shall be reflected, in particular:

- reactor type;
- thermal power;
- date of first criticality;
- presence of spent fuel storage (or shared storage).

Safety significant differences between units shall be highlighted.

The scope and main results of Probabilistic Safety Assessments shall be provided.

In a second part, each extreme situation shall be assessed following the indications given below.

Hypothesis

For existing plants, the reassessments shall refer to the plant as it is currently built and operated on June 30, 2011. For plants under construction, the reassessments shall refer to the licensed design.

The approach should be essentially deterministic: when analysing an extreme scenario, a progressive approach shall be followed, in which protective measures are sequentially assumed to be defeated.

The plant conditions should represent the most unfavourable operational states that are permitted under plant technical specifications (limited conditions for operations). All operational states should be considered. For severe accident scenarios, consideration of non-classified equipment as well as realistic assessment is possible.

All reactors and spent fuel storages shall be supposed to be affected at the same time.

Possibility of degraded conditions of the site surrounding area shall be taken into account.

Consideration should be given to:

- automatic actions;
- operators actions specified in emergency operating procedures;
- any other planned measures of prevention, recovery and mitigation of accidents;

Information to be included

Three main aspects need to be reported:

- Provisions taken in the design basis of the plant and plant conformance to its design requirements.
- Robustness of the plant beyond its design basis. For this purpose, the robustness (available design margins, diversity, redundancy, structural protection, physical separation, etc) of the safety-relevant systems, structures and components and the effectiveness of the defence-in-depth concept have to be assessed. Regarding the robustness of the installations and measures, one focus of the review is on identification of a step change in the event sequence (cliff-edge effect*****) and, if necessary, consideration of measures for its avoidance.

Any potential for modifications likely to improve the considered level of defence-in-depth, in terms of improving the resistance of components or of strengthening the independence with other levels of defence.

In addition, the licensee may wish to describe protective measures aimed at avoiding the extreme scenarios that are envisaged in the stress tests in order to provide context for the stress tests. The analysis should be complemented, where necessary, by results of dedicated plant walk down.

To this aim, the licensee shall identify:

- The means to maintain the three fundamental safety functions (control of reactivity, fuel cooling, confinement of radioactivity) and support functions (power supply, cooling through ultimate heat sink), taking into account the probable damage done by the initiating event and any means not credited in the safety demonstration for plant licensing.

**** Example : exhaustion of the capacity of the batteries in the event of a station blackout

- Possibility of mobile external means and the conditions of their use.
- Any existing procedure to use means from one reactor to help another reactor.
- Dependence of one reactor on the functions of other reactors on the same site.

As for severe accident management, the licensee shall identify, where relevant:

- The time before damage to the fuel becomes unavoidable. For PWR and BWR, if the core is in the reactor vessel, indicate time before water level reaches the top of the core, and time before fuel degradation (fast cladding oxidation with hydrogen production)
- If the fuel is in the spent fuel pool, the time before pool boiling, time up to when adequate shielding against radiation is maintained, time before water level reaches the top of the fuel elements, time before fuel degradation starts;

Supporting documentation

Documents referenced by the licensee shall be characterised either as:

- Validated in the licensing process.
- Not validated in the licensing process but gone through licensee's quality assurance program.
- Not one of the above.

Earthquake

I. Design basis

a) Earthquake against which the plant is designed:

- Level of the design basis earthquake (DBE) expressed in terms of peak ground acceleration (PGA) and reasons for the choice. Also indicate the DBE taken into account in the original licensing basis if different.
- Methodology to evaluate the DBE (return period, past events considered and reasons for choice, margins added...), validity of data in time.
- Conclusion on the adequacy of the design basis.

b) Provisions to protect the plant against the DBE

- Identification of the key structures, systems and components (SSCs) which are needed for achieving safe shutdown state and are supposed to remain available after the earthquake.
- Main operating provisions (including emergency operating procedure, mobile equipment...) to prevent reactor core or spent fuel damage after the earthquake.
- Were indirect effects of the earthquake taken into account, including:
 1. Failure of SSCs that are not designed to withstand the DBE and that, in losing their integrity could cause a consequential damage of SSCs that need to remain available (eg leaks or ruptures of non seismic pipework on the site or in the buildings as sources of flooding and their potential consequences);
 2. Loss of external power supply;
 3. Situation outside the plant, including preventing or delaying access of personnel and equipment to the site.

c) Plant compliance with its current licensing basis:

- Licensee's general process to ensure compliance (eg , periodic maintenance, inspections, testing).
- Licensee' process to ensure that off-site mobile equipment/supplies considered in emergency procedures are available and remain fit for duty.
- Any known deviation, and consequences of these deviations in terms of safety; planning of remediation actions.
- Specific compliance check already initiated by the licensee following Fukushima NPP accident.

II. Evaluation of the margins

d) Based on available information (which could include seismic PSA, seismic margin assessment or other seismic engineering studies to support engineering judgement), give an evaluation of the range of earthquake severity above which loss of fundamental safety functions or severe damage to the fuel (in vessel or in fuel storage) becomes unavoidable.

- Indicate which are the weak points and specify any cliff edge effects according to earthquake severity.
- Indicate if any provisions can be envisaged to prevent these cliff edge effects or to increase robustness of the plant (modifications of hardware, modification of procedures, organisational provisions...).

e) Based on available information (which could include seismic PSA, seismic margin assessment or other seismic engineering studies to support engineering judgement), what is the range of earthquake severity the plant can withstand without losing confinement integrity.

f) Earthquake exceeding DBE and consequent flooding exceeding DBF

- Indicate whether, taking into account plant location and plant design, such situation can be physically possible. To this aim, identify in particular if severe damages to structures that are outside or inside the plant (such as dams, dikes, plant buildings and structures) could have an impact of plant safety.
- Indicate which are the weak points and failure modes leading to unsafe plant conditions and specify any cliff edge effects. Identify which buildings and equipment will be impacted.
- Indicate if any provisions can be envisaged to prevent these cliff edge effects or to increase robustness of the plant (modifications of hardware, modification of procedures, organisational provisions...).

Flooding

I. Design basis

a) Flooding against which the plant is designed:

- Level of the design basis flood (DBF) and reasons for choice. Also indicate the DBF taken into account in the original licensing basis if different;
- Methodology to evaluate the DBF (return period, past events considered and reasons for choice, margins added...). Sources of flooding (tsunami, tidal, storm surge, breaking of dam...), validity of data in time;
- Conclusion on the adequacy of the design basis.

b) Provisions to protect the plant against the DBF

- Identification of the key SSCs which are needed for achieving safe shutdown state and are supposed to remain available after the flooding, including:
 - o Provisions to maintain the water intake function.
 - o Provisions to maintain emergency electrical power supply.
- Identification of the main design provisions to protect the site against flooding (platform level, dike...) and the associated surveillance programme if any.
- Main operating provisions (including emergency operating procedure, mobile equipment, flood monitoring, alerting systems...) to warn of, then to mitigate the effects of the flooding, and the associated surveillance programme if any.
- Were other effects linked to the flooding itself or to the phenomena that originated the flooding (such as very bad weather conditions) taken into account, including:
 - o Loss of external power supply.
 - o Situation outside the plant, including preventing or delaying access of personnel and equipment to the site.

c) Plant compliance with its current licensing basis:

- Licensee's general process to ensure compliance (e.g. periodic maintenance, inspections, testing).
- Licensee's process to ensure that off-site mobile equipment/supplies considered in emergency procedures are available and remain fit for duty.
- Any known deviation and consequences of these deviations in terms of safety; planning of remediation actions.
- Specific compliance check already initiated by the licensee following Fukushima NPP accident.

II. Evaluation of the margins

d) Based on available information (including engineering studies to support engineering judgement), what is the level of flooding that the plant can withstand without severe damage to the fuel (core or fuel storage)?

- Depending on the time between warning and flooding, indicate whether additional protective measures can be envisaged / implemented.
- Indicate which are the weak points and specify any cliff edge effects. Identify which buildings and which equipment will be flooded first.
- Indicate if any provisions can be envisaged to prevent these cliff edge effects or to increase robustness of the plant (modifications of hardware, modification of procedures, organisational provisions...).

Loss of electrical power and loss of the ultimate heat sink

Electrical AC power sources are:

- o off-site power sources (electrical grid);
- o plant generator;
- o ordinary back-up generators (diesel generator, gas turbine...);

- in some cases other diverse back-up sources.

Sequential loss of these sources has to be considered (see a) and b) below).

The ultimate heat sink (UHS) is a medium to which the residual heat from the reactor is transferred. In some cases, the plant has the primary UHS, such as the sea or a river, which is supplemented by an alternate UHS, for example a lake, a water table or the atmosphere. Sequential loss of these sinks has to be considered (see c) below).

a) Loss of off-site power (LOOP^{††††})

- Describe how this situation is taken into account in the design and describe which internal backup power sources are designed to cope with this situation.
- Indicate for how long the on-site power sources can operate without any external support.
- Specify which provisions are needed to prolong the time of on-site power supply (refuelling of diesel generators...).
- Indicate any envisaged provisions to increase robustness of the plant (modifications of hardware, modification of procedures, organisational provisions...).

For clarity, systems such as steam driven pumps, systems with stored energy in gas tanks etc. are considered to function as long as they are not dependent of the electric power sources assumed to be lost and if they are designed to withstand the initiating event (eg earthquake).

b) Loss of off-site power and of on-site backup power sources (SBO). Two situations have to be considered:

- LOOP + Loss of the ordinary back-up source;
- LOOP + Loss of the ordinary back-up sources + loss of any other diverse back- up sources.

For each of these situations:

- Provide information on the battery capacity and duration.
- Provide information on design provisions for these situations.
- Indicate for how long the site can withstand a SBO without any external support before severe damage to the fuel becomes unavoidable.
- Specify which (external) actions are foreseen to prevent fuel degradation:
 - equipment already present on-site, eg equipment from another reactor;
 - assuming that all reactors on the same site are equally damaged, equipment available off-site;
 - near-by power stations (eg hydropower, gas turbine) that can be aligned to provide power via a dedicated direct connection;
 - time necessary to have each of the above systems operating;
 - availability of competent human resources to make the exceptional connections;
 - identification of cliff edge effects and when they occur.

^{††††} All offsite electric power supply to the site is lost. The offsite power should be assumed to be lost for several days. The site is isolated from delivery of heavy material for 72 hours by road, rail or waterways. Portable light equipment can arrive to the site from other locations after the first 24 hours.

- Indicate if any provisions can be envisaged to prevent these cliff edge effects or to increase robustness of the plant (modifications of hardware, modification of procedures, organisational provisions...).

c) Loss of primary ultimate heat sink (UHS^{****})

- Provide a description of design provisions to prevent the loss of the UHS (eg various water intakes for primary UHS at different locations, use of alternative UHS, ...)

Two situations have to be considered:

- Loss of primary ultimate heat sink (UHS), i.e. access to water from the river or the sea;
- Loss of primary ultimate heat sink (UHS) and the alternate UHS.

For each of these situations:

- Indicate for how long the site can withstand the situation without any external support before damage to the fuel becomes unavoidable:
- Provide information on design provisions for these situations.
- Specify which external actions are foreseen to prevent fuel degradation:
 - o equipment already present on-site, eg equipment from another reactor;
 - o assuming that all reactors on the same site are equally damaged, equipment available off-site;
 - o time necessary to have these systems operating;
 - o availability of competent human resources;
 - o identification of cliff edge effects and when they occur.
- Indicate if any provisions can be envisaged to prevent these cliff edge effects or to increase robustness of the plant (modifications of hardware, modification of procedures, organisational provisions...).

d) Loss of the primary UHS with SBO

- Indicate for how long the site can withstand a loss of “main” UHS + SBO without any external support before severe damage to the fuel becomes unavoidable
- Specify which external actions are foreseen to prevent fuel degradation:
 - o equipment already present on-site, eg equipment from another reactor;
 - o assuming that all reactors on the same site are equally damaged, equipment available off-site;
 - o availability of human resources;
 - o time necessary to have these systems operating;
 - o identification of when the main cliff edge effects occur.

^{****} The connection with the primary ultimate heat sink for all safety and non safety functions is lost. The site is isolated from delivery of heavy material for 72 hours by road, rail or waterways. Portable light equipment can arrive to the site from other locations after the first 24 hours.

- Indicate if any provisions can be envisaged to prevent these cliff edge effects or to increase robustness of the plant (modifications of hardware, modification of procedures, organisational provisions...).

Severe accident management

This chapter deals mostly with mitigation issues. Even if the probability of the event is very low, the means to protect containment from loads that could threaten its integrity should be assessed. Severe accident management, as forming the last line of defence-in-depth for the operator, should be consistent with the measures used for preventing the core damage and with the overall safety approach of the plant.

a) Describe the accident management measures currently in place at the various stages of a scenario of loss of the core cooling function:

- before occurrence of fuel damage in the reactor pressure vessel/a number of pressure tubes;
 - o last resorts to prevent fuel damage
 - o elimination of possibility for fuel damage in high pressure
- after occurrence of fuel damage in the reactor pressure vessel/a number of pressure tubes;
- after failure of the reactor pressure vessel/a number of pressure tubes.

b) Describe the accident management measures and plant design features for protecting integrity of the containment function after occurrence of fuel damage:

- prevention of H₂ deflagration or H₂ detonation (inerting, recombiners, or igniters), also taking into account venting processes;
- prevention of over-pressurization of the containment; if for the protection of the containment a release to the environment is needed, it should be assessed, whether this release needs to be filtered. In this case, availability of the means for estimation of the amount of radioactive material released into the environment should also be described;
- prevention of re-criticality;
- prevention of basemat melt through;
- need for and supply of electrical AC and DC power and compressed air to equipment used for protecting containment integrity.

c) Describe the accident management measures currently in place to mitigate the consequences of loss of containment integrity.

d) Describe the accident management measures currently in place at the various stages of a scenario of loss of cooling function in the fuel storage (the following indications relate to a fuel pool):

- before/after losing adequate shielding against radiation;
- before/after occurrence of uncover of the top of fuel in the fuel pool;
- before/after occurrence of fuel degradation (fast cladding oxidation with hydrogen production) in the fuel pool.

For a) b) c) and d), at each stage:

- identify any cliff edge effect and evaluate the time before it;
- assess the adequacy of the existing management measures, including the procedural guidance to cope with a severe accident, and evaluate the potential for additional measures. In particular, the licensee is asked to consider:

- the suitability and availability of the required instrumentation;
- the habitability and accessibility of the vital areas of the plant (the control room, emergency response facilities, local control and sampling points, repair possibilities);
- potential H2 accumulations in other buildings than containment ;

The following aspects have to be addressed:

- Organisation of the licensee to manage the situation, including:
 - staffing, resources and shift management;
 - use of off-site technical support for accident and protection management (and contingencies if this becomes unavailable);
 - procedures, training and exercises;
- Possibility to use existing equipment;
- Provisions to use mobile devices (availability of such devices, time to bring them on-site and put them in operation, accessibility to site);
- Provisions for and management of supplies (fuel for diesel generators, water...);
- Management of radioactive releases, provisions to limit them;

Management of workers' doses, provisions to limit them;

- Communication and information systems (internal, external).

Long-term post-accident activities.

The envisaged accident management measures shall be evaluated considering what the situation could be on a site:

- Extensive destruction of infrastructure around the plant including the communication;
- Facilities (making technical and personnel support from outside more difficult);
- Impairment of work performance (including impact on the accessibility and habitability of the main and secondary control rooms, and the plant emergency/crisis centre) due to high local dose rates, radioactive;
- Contamination and destruction of some facilities on-site;
- Feasibility and effectiveness of accident management measures under the conditions of external hazards (earthquakes, floods);
- Unavailability of power supply;
- Potential failure of instrumentation;
- Potential effects from the other neighbouring plants at site.

The licensee shall identify which conditions would prevent staff from working in the main or secondary control room as well as in the plant emergency/crisis centre and what measures could avoid such conditions to occur.

ANNEX I: IAEA JAPANESE MISSION - CONCLUSIONS AND LESSONS

Table I1: IAEA Japanese Mission Report (Ref. 3) - Lessons

Lesson	Comment / Disposition
<p>Lesson 1: There is a need to ensure that in considering external natural hazards:</p> <ul style="list-style-type: none"> ■ the siting and design of nuclear plants should include sufficient protection against infrequent and complex combinations of external events and these should be considered in the plant safety analysis - specifically those that can cause site flooding and which may have longer term impacts; ■ plant layout should be based on maintaining a 'dry site concept', where practicable, as a defence-in-depth measure against site flooding as well as physical separation and diversity of critical safety systems; ■ common cause failure should be particularly considered for multiple unit sites and multiple sites, and for independent unit recovery options, utilizing all on-site resources should be provided; ■ any changes in external hazards or understanding of them should be periodically reviewed for their impact on the current plant configuration; and ■ an active tsunami warning system should be established with the provision for immediate operator action. 	<p>Looking at each bullet in turn:</p> <ul style="list-style-type: none"> ■ The Office for Nuclear Regulation's (ONR) Safety Assessment Principles (SAP) already provide sufficient guidance in this area. ■ The SAPs are not definitive in the requirement to maintain a dry site. The practicability of this is a key area. For existing sites, there is little that can be done for structures so other means to deal with flooding may be needed. This area is a candidate for review under Recommendation IR-5. ■ Common cause failure is an important consideration in the SAPs. The stress tests should explore further common cause failure for whole sites. ■ This is integral to our Periodic Safety Review (PSR) process. ■ Work by the Department for Environment, Food and Rural Affairs (Defra) in 2005/6 identified the potential for using existing monitoring equipment for this role, however this was not pursued as a practical project. The low risk and relatively benign nature of tsunami which impact the UK mean that it was not seen as a requirement.
<p>Lesson 2: For severe situations, such as total loss of off-site power or loss of all heat sinks or the engineering safety systems, simple alternative sources for these functions including any necessary equipment (such as mobile power, compressed air and water supplies) should be provided for severe accident management.</p>	<p>Recommendations IR-8, IR-18 and IR-19 are relevant here although the actual requirements for individual sites will be reviewed in detail in the "Stress Tests", which will specifically address potential improvements for loss of off-site power and loss of heat sinks.</p>

Table I1: IAEA Japanese Mission Report (Ref. [3](#)) - Lessons

Lesson	Comment / Disposition
<p>Lesson 3: Such provisions as are identified in Lesson 2 should be located at a safe place and the plant operators should be trained to use them. This may involve centralized stores and means to rapidly transfer them to the affected site(s).</p>	<p>Again this is related to Recommendations IR-8, IR-18 and IR-19. Recommendation IR-8 has been augmented to include a review of the need for provision and safe storage off-site of equipment to support the site response to an accident. Consideration of the timescales to transfer off-site equipment or supplies to the site.</p>
<p>Lesson 4: Nuclear sites should have adequate on-site seismically robust, suitably shielded, ventilated and well equipped buildings to house the Emergency Response Centres, with similar capabilities to those provided at Fukushima Dai-ni [Fukushima-1] and Dai-ichi [Fukushima-2], which are also secure against other external hazards such as flooding. They will require sufficient provisions and must be sized to maintain the welfare and radiological protection of workers needed to manage the accident.</p>	<p>This lesson is captured within Recommendations IR-22 and IR-23. The recommendation places requirements upon the UK Nuclear Industry with regard to Emergency Control Centre, Instrumentation and Communications.</p>

Table 11: IAEA Japanese Mission Report (Ref. 3) - Lessons

Lesson	Comment / Disposition
<p>Lesson 5: Emergency Response Centres should have available as far as practicable essential safety-related parameters based on hardened instrumentation and lines such as coolant levels, containment status, pressure, etc., and have sufficient secure communication lines to control rooms and other places on-site and off-site.</p>	<p>This is essentially covered by Recommendation IR-22, though we have added new information covering specific details to reflect the content of this lesson.</p>
<p>Lesson 6: Severe Accident Management Guidelines and associated procedures should take account of the potential unavailability of instruments, lighting, power and abnormal conditions including plant state and high radiation fields.</p>	<p>Work underway to address Recommendations IR-22 and IR-24 will take account of this lesson.</p>
<p>Lesson 7: External events have a potential of affecting several plants and several units at the plants at the same time. This requires a sufficiently large resource in terms of trained experienced people, equipment, supplies and external support. An adequate pool of experienced personnel who can deal with each type of unit and can be called upon to support the affected sites should be ensured.</p>	<p>This lesson is already captured within Recommendations IR-3, IR-6 and IR-24.</p>
<p>Lesson 8: The risk and implications of hydrogen explosions should be revisited and necessary mitigating systems should be implemented.</p>	<p>The need to review hydrogen explosions is accepted and is an integral part of the European Council “Stress Tests”. We have also added new information to clarify Recommendation IR-25 in respect of severe accidents.</p>
<p>Lesson 9: Particularly in relation to preventing loss of safety functionality, the robustness of defence-in-depth against common cause failure should be based on providing adequate diversity (as well as redundancy and physical separation) for essential safety functions.</p>	<p>ONR’s SAPs are very clear on the importance of defence-in-depth and its role in combating common cause failure. Nevertheless, we recognise that the need for additional measures will be thoroughly explored in the “Stress Tests” and feed into our work under Recommendation IR-5.</p>
<p>Lesson 10: Greater consideration should be given to providing hardened systems, communications and sources of monitoring equipment for providing essential information for on-site and off-site responses, especially for severe accidents.</p>	<p>This will be a key feature of work to take forward Recommendation IR-22. In this report we have added new information to clarify the recommendation.</p>

Table I1: IAEA Japanese Mission Report (Ref. [3](#)) - Lessons

Lesson	Comment / Disposition
<p>Lesson 11: The use of IAEA Safety Requirements (such as GS-R-2) and related guides on threat categorization, event classification and countermeasures, as well as Operational Intervention Levels, could make the off-site emergency preparedness and response even more effective in particular circumstances.</p>	<p>The Nuclear Emergency Planning Liaison Group (NEPLG) Legislation sub group will provide the mechanism within the UK to provide review and update to the International Atomic Energy Agency (IAEA) document entitled Preparedness and Response for a Nuclear or Radiological Emergency” (GS-R-2) and in particular its supporting guidance entitled “<i>Arrangements for Preparedness for a Nuclear or Radiological Emergency</i>” (GS-G-2.1). Whilst it is considered that there will be little change of substance to the requirements in GS-R-2 there will be substantial revision to GS-G-2.1 in the light of the lessons being learned from Fukushima (that is in how the requirements are actually delivered). Consequently this highlights the importance of the work of ONR identified prior to the Fukushima accident which is being progressed by the NEPLG Legislation Subgroup. This work will underpin the UK position that will be adopted for the reviews of GS-R-2 and GS-G-2.1.</p>
<p>Lesson 12: The use of long term sheltering is not an effective approach and has been abandoned and concepts of ‘deliberate evacuation’ and ‘evacuation-prepared area’ were introduced for effective long term countermeasures using guidelines of the ICRP and IAEA. IAEA.</p>	<p>This is essentially covered by comments on Lesson 11 above.</p>

Table I1: IAEA Japanese Mission Report (Ref. [3](#)) - Lessons

Lesson	Comment / Disposition
<p>Lessons 13: The international nuclear community should take advantage of the data and information generated from the Fukushima accident to improve and refine the existing methods and models to determine the source term involved in a nuclear accident and refine emergency planning arrangements.</p>	<p>The comments on Lesson 11 are also relevant here, and we have introduced new recommendations on source term estimation (FR-6) and prediction of doses to the public to support decisions on off-site countermeasures (FR-7).</p>
<p>Lesson 14: Large scale radiation protection for workers on sites under severe accident conditions can be effective if appropriately organized and with well led and suitable trained staff.</p>	<p>This is broadly covered by Recommendations IR-3 and IR-6. Updates on the position with respect to these recommendations are given in the main text of this report.</p>
<p>Lesson 15: Exercises and drills for on-site workers and external responders in order to establish effective on-site radiological protection in severe accident conditions would benefit from taking account of the experiences at Fukushima.</p>	<p>As for Lesson 14 above, this is broadly covered by Recommendations IR-3 and IR-6. Updates on the position with respect to these recommendations are given in the main text of this report.</p>
<p>Lesson 16: Nuclear regulatory systems should ensure that regulatory independence and clarity of roles are preserved in all circumstances in line with IAEA Safety Standards.</p>	<p>Every regulatory model has to take account of the particular legal, governmental, industrial and cultural environment in which it operates. In the UK this results in a goal setting approach with the clear roles and responsibilities of all including that of the independent expert nuclear regulator to secure the protection of people and society from activities of the nuclear industry. Such clarity and separation of roles and responsibilities is essential, even during emergency situations, in earning the trust and the confidence of the public. The recent creation of ONR as a non-statutory agency of HSE will enhance ONR's regulatory independence, and the Government's intention to create ONR as a statutory corporation in the future will enhance this even further.</p>

ANNEX J: JAPANESE GOVERNMENT REPORT TO IAEA – LESSONS

Table J1: Japanese Government Report to IAEA (Ref. [2](#)) - Lessons

Lesson	Comment / Disposition
Lessons in Category 1 - Strengthen preventive measures against a severe accident	
<p>(1) Strengthen measures against earthquakes and tsunamis</p> <p>The earthquake was an extremely massive one caused by plurally linked seismic centers. As a result, at the Fukushima Dai-ichi [Fukushima-1] Nuclear Power Station, the acceleration response spectra of seismic ground motion observed on the base mat exceeded the acceleration response spectra of the design basis seismic ground motion in a part of the periodic band. Although damage to the external power supply was caused by the earthquake, no damage caused by the earthquake to systems, equipment or devices important for nuclear reactor safety at nuclear reactors has been confirmed. However, further investigation should be conducted as the details regarding this situation remain unknown.</p> <p>The tsunamis which hit the Fukushima Dai-ichi [Fukushima-1] Nuclear Power Station were 14-15m high, substantially exceeding the height assumed under the design of construction permit or the subsequent evaluation. The tsunamis severely damaged seawater pumps, etc., causing the failure to secure the emergency diesel power supply and reactor cooling function. The procedural manual did not assume flooding from a tsunami, but rather only stipulated measures against a backrush. The assumption on the frequency and height of tsunamis was insufficient, and therefore, measures against large-scale tsunamis were not prepared adequately.</p> <p>From the viewpoint of design, the range of an active period for a capable fault which needs to be considered in the seismic design for a nuclear power plant is considered within 120,000-130,000 years (50,000 years in the old guideline). The recurrence of</p>	<p>There are several points raised here:</p> <ul style="list-style-type: none"> ■ The design basis event should be characterised on a return frequency basis, not on “folk law”. ■ In assessing the seismic activity of a fault, historical and pre-historical investigations should be undertaken. ■ The effects of external hazards on off-site power supplies should be considered and necessary strengthening of supplies provided. ■ There should be a consideration of beyond design basis events. ■ The full effects of tsunami should be considered, including destructive effects other than simply inundation. <p>We are in the process of developing criteria for assessing the potential for activity of identified faults. This will form part of our supporting guidance to ONR’s SAPs.</p>

Table J1: Japanese Government Report to IAEA (Ref. [2](#)) - Lessons

Lesson	Comment / Disposition
<p>large-scale earthquakes is expected to be appropriately considered. Moreover, residual risks must be considered. Compared with the design against earthquake, the design against tsunamis has been performed based on tsunami folklore and indelible traces of tsunami, not on adequate consideration of the recurrence of large-scale earthquakes in relation to a safety goal to be attained.</p> <p>Reflecting on the above issues, we will consider the handling of plurally linked seismic centers as well as the strengthening of the quake resistance of external power supplies. Regarding tsunamis, from the viewpoint of preventing a severe accident, we will assume appropriate frequency and adequate height of tsunamis in consideration of a sufficient recurrence period for attaining a safety goal. Then, we will perform a safety design of structures, etc. to prevent the impact of flooding of the site caused by tsunamis of adequately assumed heights, in consideration of the destructive power of tsunamis. While fully recognizing a possible risk caused by the flooding into buildings of tsunamis exceeding the ones assumed in design, we will take measures from the viewpoint of having defenses-in-depth, to sustain the important safety functions by considering flooded sites and the huge destructive power of run-up waves.</p>	

Table J1: Japanese Government Report to IAEA (Ref. [2](#)) - Lessons

Lesson	Comment / Disposition
<p>(2) Ensure power supplies</p> <p>A major cause of this accident was the failure to secure the necessary power supply. This was caused by the facts that power supply sources were not diversified from the viewpoint of overcoming vulnerability related to failures derived from a common cause arising from an external event, and that the installed equipment such as a switchboard did not meet the specifications that could withstand a severe environment such as flooding. Moreover, it was caused by the facts that battery life was short compared with the time required for restoration of the AC power supply and that a time goal required for the recovery of the external power supply was not clear.</p> <p>Reflecting on the above facts, Japan will secure a power supply at sites for a longer time set forth as a goal even in severe circumstances of emergencies, through the diversification of power supply sources by preparing various emergency power supply sources such as air-cooled diesel generators, gas turbine generators, etc., deploying power-supply vehicles and so on, as well as equipping switchboards, etc. with high environmental tolerance and generators for battery charging, and so on.</p>	<p>This is clearly an important lesson and links to Recommendations IR-17 and IR-18.</p>

Table J1: Japanese Government Report to IAEA (Ref. [2](#)) - Lessons

Lesson	Comment / Disposition
<p>(3) Ensure robust cooling functions of reactors and PCVs</p> <p>In this accident, the final place for release of heat (the final heat sink) was lost due to the loss of function of the seawater pumps. Although the reactor cooling function of water injection was activated, core damage could not be prevented due to the drain of the water source for injection and the loss of power supplies, etc., and furthermore, the PCV cooling functions also failed to run well. Thereafter, difficulties remained in reducing the reactor pressure and, moreover, in injecting water after the pressure was reduced, because the water injection line into a reactor through the use of heavy machinery such as fire engines, etc. had not been developed as measures for accident management. In this manner, the loss of cooling functions of the reactors and PCVs aggravated the accident.</p> <p>Reflecting on the above issues, Japan will secure robust alternative cooling functions for its reactors and PCVs by securing alternative final heat sinks for a durable time. This will be pursued through such means as diversifying alternative water injection functions, diversifying and increasing sources for injection water, and introducing air-cooling systems.</p>	<p>Some elements of this lesson are covered in Recommendations IR-13, IR-18 and IR-19. In light of this lesson we have added further information to clarify Recommendation IR-13 to include:</p> <ul style="list-style-type: none"> ■ Capability to repair and availability of spare parts and components. ■ Review strategies and contingency measures for situations when the main lines of defence are lost.

Table J1: Japanese Government Report to IAEA (Ref. [2](#)) - Lessons

Lesson	Comment / Disposition
<p>(4) Ensure robust cooling functions of spent fuel pools</p> <p>In the accident, the loss of power supplies caused the failure to cool the spent fuel pools, requiring actions to prevent a severe accident due to the loss of cooling functions of the spent fuel pools concurrently with responses to the accident of the reactors. Until now, a risk of a major accident of a spent fuel pool had been deemed small compared with that of a core event and measures such as alternative means of water injection into spent fuel pools, etc. had not been considered.</p> <p>Reflecting on the above issues, Japan will secure robust cooling measures by introducing alternative cooling functions such as a natural circulation cooling system or an air-cooling system, as well as alternative water injection functions in order to maintain the cooling of spent fuel pools even in case of the loss of power supplies.</p>	<p>This is linked to Recommendation IR-20, and worth noting that in the UK spent fuel pool risks have always been regarded as potentially significant and hence taken fully into account.</p> <p>Spent fuel pool cooling functions are an explicit part of the “Stress Tests” and further lessons may arise from that process.</p>

Table J1: Japanese Government Report to IAEA (Ref. [2](#)) - Lessons

Lesson	Comment / Disposition
<p>(5) Thorough accident management (AM) measures</p> <p>The accident reached the level of a so-called “severe accident.” Accident management measures had been introduced to the Fukushima NPSs to minimize the possibilities of severe accidents and to mitigate consequences in the case of severe accidents. However, looking at the situation of the accident, although some portion of the measures functioned, such as the alternative water injection from the fire extinguishing water system to the reactor, the rest did not fulfill their roles within various responses including ensuring the power supplies and the reactor cooling function, with the measures turning out to be inadequate. In addition, accident management measures are basically regarded as voluntary efforts by operators, not legal requirements, and so the development of these measures lacked strictness. Moreover, the guideline for accident management has not been reviewed since its development in 1992, and has not been strengthened or improved.</p> <p>Reflecting on the above issues, we will change the accident management measures from voluntary safety efforts by operators to legal requirements, and develop accident management measures to prevent severe accidents, including a review of design requirements as well, by utilizing a probabilistic safety assessment approach.</p>	<p>The revision of the contingency plans and training for severe accidents is covered in Recommendation IR-24 and the use of Probabilistic Safety Analysis (PSA) to support accident management programme enhancements is part of Recommendation IR-25. We have added further detail to Recommendation IR-25 and introduced a new specific PSA recommendation, Recommendation FR-4.</p>

Table J1: Japanese Government Report to IAEA (Ref. [2](#)) - Lessons

Lesson	Comment / Disposition
<p>(6) Response to issues concerning the siting with more than one reactor</p> <p>The accident occurred at more than one reactor at the same time, and the resources needed for accident response had to be dispersed. Moreover, as two reactors shared the facilities, the physical distance between the reactors was small and so on. The development of an accident occurring at one reactor affected the emergency responses at nearby reactors.</p> <p>Reflecting on the above issues, Japan will take measures to ensure that emergency operations at a reactor where an accident occurs can be conducted independently from operation at other reactors if one power station has more than one reactor. Also, Japan will assure the engineering independence of each reactor to prevent an accident at one reactor from affecting nearby reactors. In addition, Japan will promote the development of a structure that enables each unit to carry out accident responses independently, by choosing a responsible person for ensuring the nuclear safety of each unit.</p>	<p>This is covered by Recommendation IR-11.</p>
<p>(7) Consideration of NPS arrangement in basic designs</p> <p>Response to the accident became difficult since the spent fuel storage pools were located at a higher part of the reactor buildings. In addition, contaminated water from the reactor buildings reached the turbine buildings, meaning that the spread of contaminated water to other buildings has not been prevented. .</p> <p>Reflecting on the above issues, Japan will promote the adequate placement of facilities and buildings at the stage of basic design of NPS arrangement, etc. in order to further ensure the conducting of robust cooling, etc. and prevent an expansion of impacts from the accident, in consideration of the occurrence of serious accidents. In this regard, as for existing facilities, additional response measures will be taken to add equivalent levels of functionality to them.</p>	<p>This is covered by Recommendations IR-19 and IR-20.</p>

Table J1: Japanese Government Report to IAEA (Ref. [2](#)) - Lessons

Lesson	Comment / Disposition
<p>(8) Ensuring the water tightness of essential equipment facilities</p> <p>One of the causes of the accidents is that the tsunami flooded many essential equipment facilities including the component cooling seawater pump facilities, the emergency diesel generators, the switchboards, etc., impairing power supply and making it difficult to ensure cooling systems.</p> <p>Reflecting on the above issues, in terms of achieving the target safety level, Japan will ensure the important safety functions even in the case of tsunamis greater than ones expected by the design or floods hitting facilities located near rivers. In concrete terms, Japan will ensure the water-tightness of important equipment facilities by installing watertight doors in consideration of the destructive power of tsunamis and floods, blocking flooding routes such as pipes, and installing drain pumps, etc.</p>	<p>The need to consider beyond Design Basis Accidents (DBA) is already addressed within ONR's SAPs and Technical Assessment Guides (TAG). The lesson is relevant to our Recommendations IR-10 and IR-13.</p>

Table J1: Japanese Government Report to IAEA (Ref. [2](#)) - Lessons

Lesson	Comment / Disposition
Lessons in Category 2 - Enhancement of response measures against severe accidents	
<p>(9) Enhancement of measures to prevent hydrogen explosions</p> <p>In the accident, an explosion probably caused by hydrogen occurred at the reactor building in Unit 1 at 15:36 on March 12, 2011, as well as at the reactor in Unit 3 at 11:01 on March 14. In addition, an explosion that was probably caused by hydrogen occurred at the reactor building in Unit 4 around 06:00 on March 15, 2011. Consecutive explosions occurred as effective measures could not be taken beginning from the first explosion. These hydrogen explosions aggravated the accident. A BWR inactivates a PCV and has a flammability control system in order to maintain the soundness of the PCV against design basis accidents. However, it was not assumed that an explosion in reactor buildings would be caused by hydrogen leakage, and as a matter of course, hydrogen measures for reactor buildings were not taken.</p> <p>Reflecting on the above issues, we will enhance measures to prevent hydrogen explosions such as by installing of flammability control systems that would function in the event of a severe accident in reactor buildings, for the purpose of discharging or reducing hydrogen in the reactor buildings, in addition to measures to address hydrogen within the PCVs.</p>	<p>This lesson addresses the management of severe accident hydrogen phenomena which is applicable to Sizewell B, at least, and hydrogen accumulation is relevant to other nuclear installations in the UK. Rather than a specific hydrogen related recommendation we have augmented Recommendation IR-25 to cover severe accident preparedness.</p>

Table J1: Japanese Government Report to IAEA (Ref. [2](#)) - Lessons

Lesson	Comment / Disposition
<p>(10) Enhancement of containment venting system</p> <p>In the accident, there were problems in the operability of the containment venting system. Also, as the function of removing released radioactive materials in the containment venting system was insufficient, the system was not effective as an accident management countermeasure. In addition, the independence of the vent line was insufficient and it may have had an adverse effect on other parts through connecting pipes, etc.</p> <p>Reflecting on the above issues, we will enhance the containment venting system by improving its operability, ensuring its independence, and strengthening its function of removing released radioactive materials.</p>	<p>This is largely covered by Recommendation IR-21 and the enhancement to Recommendation IR-25 noted in relation to Lesson 9 above.</p>
<p>(11) Improvements to the accident response environment</p> <p>In the accident, the radiation dosage increased in the main control room and operators could not enter the room temporarily and the habitability in the main control room has decreased, as it still remains difficult to work in that room for an extended period. Moreover, at the on-site emergency station, which serves as a control tower for all emergency measures at the site, the accident response activities were affected by increases in the radiation dosage as well as by the worsening of the communication environment and lighting.</p> <p>Reflecting on the above issues, we will enhance the accident response environment that enables continued accident response activities even in case of severe accidents through measures such as strengthening radiation shielding in the control rooms and the emergency centers, enhancing the exclusive ventilation and air conditioning systems on site, as well as strengthening related equipment, including communication and lightening systems, without use of AC power supply.</p>	<p>This lesson links to Recommendations IR-22 and IR-23.</p>

Table J1: Japanese Government Report to IAEA (Ref. [2](#)) - Lessons

Lesson	Comment / Disposition
<p>(12) Enhancement of the radiation exposure management system at the time of the accident</p> <p>As these accidents occurred, although adequate radiation management became difficult as many of the personal dosimeters and dose reading devices became unusable due to their submergence in seawater, personnel engaged in radiation work had to work on site. In addition, measurements of concentration of radioactive materials in the air were delayed, and as a result the risk of internal exposure increased.</p> <p>Reflecting on the above issues, we will enhance the radiation exposure management system at the time of an accident occurs by storing the adequate amount of personal dosimeters and protection suits and gears for accidents, developing a system in which radioactive management personnel can be expanded at the time of the accident and improving the structures and equipment by which the radiation doses of radiation workers are measured promptly.</p>	<p>At the time that the Interim Report was prepared there was incomplete information available in this area (e.g. see paragraph 419). In this Final Report, the further available information has been considered (see the Section "Doses to Intervention Personnel") and Recommendation IR-22 has been augmented to ensure that full advantage can be taken of the experience gained.</p>

Table J1: Japanese Government Report to IAEA (Ref. [2](#)) - Lessons

Lesson	Comment / Disposition
<p>(13) Enhancement of training responding to severe accidents</p> <p>Effective training to respond to accident restoration at nuclear power plants and adequately work and communicate with relevant organizations in the wake of severe accidents was not sufficiently implemented up to now. For example, it took time to establish communication between the emergency office inside the power station, the Nuclear Emergency Response Headquarters and the Local Headquarters and also to build a collaborative structure with the Self Defense Forces, the Police, Fire Authorities and other organizations which played important roles in responding to the accident. Adequate training could have prevented these problems.</p> <p>Reflecting on the above issues, we will enhance training to respond to severe accidents by promptly building a structure for responding to accident restoration, identifying situations within and outside power plants, facilitating the gathering of human resources needed for securing the safety of residents and collaborating effectively with relevant organizations.</p>	<p>This lesson links to Recommendations IR-3, IR-6 and IR-24.</p>
<p>(14) Enhancement of instrumentation to identify the status of the reactors and PCVs</p> <p>Because the instrumentation of the reactors and PCVs did not function sufficiently during the severe accident, it was difficult to promptly and adequately obtain important information to identify how the accident was developing such as the water levels and the pressure of reactors, and the sources and amounts of released radioactive materials.</p> <p>In respond to the above issues, we will enhance the instrumentation of reactors and PCVs, etc. to enable them to function effectively even in the wake of severe accidents.</p>	<p>This lesson links to Recommendation IR-22, to which further information has been added to clarify the recommendation, and the new recommendations Recommendations FR-2 and FR-3.</p>

Table J1: Japanese Government Report to IAEA (Ref. [2](#)) - Lessons

Lesson	Comment / Disposition
<p>(15) Central control of emergency supplies and equipment and setting up rescue team</p> <p>Logistic support has been provided diligently by those responding to the accident and supporting affected people with supplies and equipment gathered mainly at J Village. However, because of the damage from the earthquake and tsunami in the surrounding areas shortly after the accident, we could not promptly or sufficiently mobilize rescue teams to help provide emergency supplies and equipment or support accident control activities. This is why the on-site accident response did not sufficiently function.</p> <p>Reflecting on the above issues, we will introduce systems for centrally controlling emergency supplies and equipment and setting up rescue teams for operating such systems in order to provide emergency support smoothly even under harsh circumstances.</p>	<p>This is similar to the comments on Lesson 12 above. Further information has been added to clarify Recommendation IR-22 in the light of this.</p>

Table J1: Japanese Government Report to IAEA (Ref. [2](#)) - Lessons

Lesson	Comment / Disposition
Lessons in Category 3 - Enhancement of nuclear emergency responses	
<p>(16) Responses to combined emergencies of both large-scale natural disasters and prolonged nuclear accident</p> <p>There was tremendous difficulty in communication and telecommunications, mobilizing human resources, and procuring supplies among other areas when addressing the nuclear accident that coincided with a massive natural disaster. As the nuclear accident has been prolonged, some measures such as the evacuation of residents, which was originally assumed to be a short-term measure, have been forced to be extended.</p> <p>Reflecting on the above issues, we will prepare the structures and environments where appropriate communication tools and devices and channels to procure supplies and equipment will be ensured in the case of concurrent emergencies of both a massive natural disaster and a prolonged nuclear accident. Also, assuming a prolonged nuclear accident, we will enhance emergency response preparedness including effective mobilization plans to gather human resources in various fields who are involved with accident response and support for affected persons.</p>	<p>This lesson links to Recommendations IR-3, IR-6 and IR-24.</p>

Table J1: Japanese Government Report to IAEA (Ref. [2](#)) - Lessons

Lesson	Comment / Disposition
<p>(17) Reinforcement of environmental monitoring</p> <p>Currently, local governments are responsible for environmental monitoring in an emergency. However, appropriate environmental monitoring was not possible immediately after the accident because the equipment and facilities for environmental monitoring owned by local governments were damaged by the earthquake and tsunami and the relevant individuals had to evacuate from the Off-site Center Emergency Response Center. To bridge these gaps, MEXT has conducted environmental monitoring in cooperation with relevant organizations.</p> <p>Reflecting on the above issues, the Government will develop a structure through which the Government will implement environmental monitoring in a reliable and well-planned manner during emergencies.</p>	<p>This lesson links to Recommendations IR-3, IR-6 and IR-24.</p>

Table J1: Japanese Government Report to IAEA (Ref. [2](#)) - Lessons

Lesson	Comment / Disposition
<p>(18) Establishment of a clear division of labor between relevant central and local organizations</p> <p>Communication between local and central offices as well as with other organizations was not achieved to a sufficient degree, due to the lack of communication tools immediately after the accident and also due to the fact that the roles and responsibilities of each side were not clearly defined. Specifically, responsibility and authority were not clearly defined in the relationship between the NERHQs Nuclear Emergency Response Headquarters and Local NERHQs Headquarters, between the Government and TEPCO, between the Head Office of TEPCO and the NPS on site, or among the relevant organizations in the Government. Especially, communication was not sufficient between the government and the main office of TEPCO as the accident initially began to unfold.</p> <p>Reflecting on the above issues, we will review and define roles and responsibilities of relevant organizations including the NERHQs, clearly specify roles, responsibilities and tools for communication while also improving institutional mechanisms.</p>	<p>This lesson links to Recommendations IR-2 and IR-3.</p>

Table J1: Japanese Government Report to IAEA (Ref. [2](#)) - Lessons

Lesson	Comment / Disposition
<p>(19) Enhancement of communication relevant to the accident</p> <p>Communication to residents in the surrounding area was difficult because communication tools were damaged by the large-scale earthquake. The subsequent information to residents in the surrounding area and local governments was not always provided in a timely manner. The impact of radioactive materials on health and the radiological protection guidelines of the ICRP, which are the most important information for residents in the surrounding area and others, were not sufficiently explained. Japan focused mainly on making accurate facts publicly available to its citizens and has not sufficiently presented future outlooks on risk factors, which sometimes gave rise to concerns about future prospects.</p> <p>Reflecting on the above issues, we will reinforce the adequate provision of information on the accident status and response, along with appropriate explanations of the effects of radiation to the residents in the vicinity. Also, we will keep in mind having the future outlook on risk factors is included in the information delivered while incidents are still ongoing.</p>	<p>This is covered by the UK Government response to Interim Report Recommendations IR-1 and IR-2.</p>

Table J1: Japanese Government Report to IAEA (Ref. [2](#)) - Lessons

Lesson	Comment / Disposition
<p>(20) Enhancement of responses to assistance from other countries and communication to the international community</p> <p>The Japanese Government could not appropriately respond to the assistance offered by countries around the world because no specific structure existed within the Government to link such assistance offered by other countries to the domestic needs. Also, communication with the international community including prior notification to neighboring countries and areas on the discharge of water with low-level radioactivity to the sea was not always sufficient.</p> <p>Reflecting on the above-mentioned issues, the Japanese Government will contribute to developing a global structure for effective responses, by cooperating with the international community, for example, developing a list of supplies and equipment for effective responses to any accident, specifying contact points for each country in advance in case of an accident, enhancing the information sharing framework through improvements to the international notification system, and providing faster and more accurate information to enable the implementation of measures that are based upon scientific evidence.</p>	<p>This lesson links to Recommendations IR-1 and IR-2.</p>

Table J1: Japanese Government Report to IAEA (Ref. [2](#)) - Lessons

Lesson	Comment / Disposition
<p>(21) Adequate identification and forecasting of the effect of released radioactive materials</p> <p>The System for Prediction of Environmental Emergency Dose Information (SPEEDI) could not make proper predictions on the effect of radioactive materials as originally designed, due to the lack of information on release sources. Even under such restricted conditions, it should have been utilized, as a reference of evacuation activities and other purposes by presuming diffusion trends of radioactive materials under certain assumptions. Although the results generated by SPEEDI are now being disclosed, disclosure should have been conducted from the initial stage.</p> <p>The Japanese Government will improve its instrumentation and facilities to ensure that release source information can be securely obtained. Also, it will develop a plan to effectively utilize SPEEDI and other systems to address various emergent cases and disclose the data and results from SPEEDI, etc. from the earliest stages of such cases.</p>	<p>The UK has a very well developed rationale and arrangements for off-site assessment, response and countermeasures, which are explained in Annex D. Nevertheless, it was recognised in the Interim Report that the experience from Fukushima would be valuable in reviewing and refining this, particularly in view of the extended nature of the emergency phase and the impact of infrastructure disruption, leading to Recommendations IR-2 and IR-3. Progress on these issues is described in the main text of this report.</p>

Table J1: Japanese Government Report to IAEA (Ref. [2](#)) - Lessons

Lesson	Comment / Disposition
<p>(22) Clear definition of widespread evacuation areas and radiological protection guidelines in nuclear emergency</p> <p>Immediately after the accident, an Evacuation Area and In-house Evacuation Area were established, and cooperation of residents in the vicinity, local governments, police and relevant organizations facilitated the fast implementation of evacuation and “stay-in-house” instruction. As the accident became prolonged, the residents had to be evacuated or stay within their houses for long periods. Subsequently, however, it was decided that guidelines of the ICRP and IAEA, which have not been used before the accident, would be used when establishing Deliberate Evacuation Area and Emergency Evacuation Prepared Area. The size of the protected area defined after the accident was considerably larger than a 8 to 10 km radius from the NPS, which had been defined as the area where focused protection measures should be taken.</p> <p>Based on the experiences gained from the accident, the Japanese Government will make much greater efforts to clearly define evacuation areas and guidelines for radiological protection in nuclear emergencies.</p>	<p>This is covered by comments on Lesson 21 above.</p>

Table J1: Japanese Government Report to IAEA (Ref. [2](#)) - Lessons

Lesson	Comment / Disposition
Lessons in Category 4 - Reinforcement of safety infrastructure	
<p>(23) Reinforcement of safety regulatory bodies</p> <p>Governmental organizations have different responsibilities for securing nuclear safety. For example, NISA of METI is responsible for safety regulation as a primary regulatory body, while the Nuclear Safety Commission of the Cabinet Office is responsible for regulation monitoring of the primary governmental body, and relevant local governments and ministries are in charge of emergency environmental monitoring. This is why it was not clear where the primary responsibility lies in ensuring citizens' safety in an emergency. Also, we cannot deny that the existing organizations and structures hindered the mobilization of capabilities in promptly responding to such a large-scale nuclear accident.</p> <p>Reflecting on the above issues, the Japanese Government will separate NISA from METI and start to review implementing frameworks, including the NSC and relevant ministries, for the administration of nuclear safety regulations and for environmental monitoring.</p>	<p>This was dealt with in the Interim Report, which notes that the UK regulators already operate independently of Government and the industry. The Interim Report also notes that the intention is to further enhance the independence of ONR.</p>

Table J1: Japanese Government Report to IAEA (Ref. [2](#)) - Lessons

Lesson	Comment / Disposition
<p>(24) Establishment and reinforcement of legal structures, criteria and guidelines</p> <p>Reflecting on this accident, various challenges have been identified regarding the establishment and reinforcement of legal structures on nuclear safety and nuclear emergency preparedness and response, and related criteria and guidelines. Also, based on the experiences of this nuclear accident, many issues will be identified as ones to be reflected in the standards and guidelines of the IAEA.</p> <p>Therefore, the Japanese Government will review and improve the legal structures governing nuclear safety and nuclear emergency preparedness and response, along with related criteria and guidelines. During this process, it will reevaluate measures taken against age-related degradation of existing facilities, from the viewpoint of structural reliability as well as the necessity of responding to new knowledge and expertise including progress in system concepts. Also, the Japanese Government will clarify technical requirements based on new laws and regulations or on new findings and knowledge for facilities that have already been approved and licensed, in other words, it will clarify the status of retrofitting in the context of the legal and regulatory framework. The Japanese Government will make every effort to contribute to improving safety standards and guidelines of the IAEA by providing related data.</p>	<p>This is linked to comments against Lesson 23 above.</p>

Table J1: Japanese Government Report to IAEA (Ref. [2](#)) - Lessons

Lesson	Comment / Disposition
<p>(25) Human resources for nuclear safety and nuclear emergency preparedness and responses</p> <p>All the experts on severe accidents, nuclear safety, nuclear emergency preparedness and response, risk management and radiation medicine should get together to address such an accident by making use of the latest and best knowledge and experience. Also, it is extremely important to develop human resources in the fields of nuclear safety and nuclear emergency preparedness and response in order to ensure mid-and-long term efforts on nuclear safety as well as to bring restoration to the current accident.</p> <p>Reflecting on the above-mentioned issues, the Japanese Government will enhance human resource development within the activities of nuclear operators and regulatory organizations along with focusing on nuclear safety education, nuclear emergency preparedness and response, crisis management and radiation medicine at educational organizations.</p>	<p>This lesson links to Recommendations IR-3, IR-6 and IR-24.</p>
<p>(26) Ensuring the independence and diversity of safety systems</p> <p>Although multiplicity has been valued until now in order to ensure the reliability of safety systems, avoidance of common cause failures has not been carefully considered and independence and diversity have not been sufficiently secured.</p> <p>Therefore, the Japanese Government will ensure the independence and diversity of safety systems so that common cause failures can be adequately addressed and the reliability of safety functions can be further improved.</p>	<p>ONR's existing SAPs do cover all of these items in some detail. Nevertheless, we will be open to further improvements as a possible outcome of our work under Interim Report Recommendation IR-5.</p>

Table J1: Japanese Government Report to IAEA (Ref. [2](#)) - Lessons

Lesson	Comment / Disposition
<p>(27) Effective use of probabilistic safety assessment (PSA) in risk management</p> <p>PSA has not always been effectively utilized in the overall reviewing processes or in risk reduction efforts at nuclear power plants. While a quantitative evaluation of risks of quite rare events such as a large-scale tsunami is difficult and may be associated with uncertainty even within PSA, Japan has not made sufficient efforts to improve the reliability of the assessments by explicitly identifying the uncertainty of these risks.</p> <p>Considering knowledge and experiences regarding uncertainties, the Japanese Government will further actively and swiftly utilize PSA while developing improvements to safety measures including effective accident management measures based on PSA.</p>	<p>This is an important lesson, acknowledging that effective use of PSA could have helped help to prevent accidents like that at Fukushima escalating, and to help deal with them should they occur. We have included a new recommendation, Recommendation FR-4 to cover this point.</p>

Table J1: Japanese Government Report to IAEA (Ref. [2](#)) - Lessons

Lesson	Comment / Disposition
Lessons in Category 5 - Thoroughly instil a safety culture	
<p>(28) Thoroughly instil a safety culture</p> <p>All those involved with nuclear energy should be equipped with a safety culture. “Nuclear safety culture” is stated as “A safety culture that governs the attitudes and behavior in relation to safety of all organizations and individuals concerned must be integrated in the management system.” (IAEA, Fundamental Safety Principles, SF-1, 3.13) Learning this message and putting it into practice is the starting point, the duty and the responsibility of those who are involved with nuclear energy. Without a safety culture, there will be no continual improvement of nuclear safety.</p> <p>Reflecting on the current accident, the nuclear operators whose organization and individuals have primary responsibility for securing safety should look at every knowledge and every finding, and confirm whether or not they indicate a vulnerability of a plant. They should reflect as to whether they have been serious in introducing appropriate measures for improving safety, when they are not confident that risks concerning the public safety of the plant remain low.</p> <p>Also, organizations or individuals involved in national nuclear regulations, as those who responsible for ensuring the nuclear safety of the public, should reflect whether they have been serious in addressing new knowledge in a responsive and prompt manner, not leaving any doubts in terms of safety.</p> <p>Reflecting on this viewpoint, Japan will establish a safety culture by going back to the basics, namely that pursuing defenses-in-depth is essential for ensuring nuclear safety, by constantly learning professional knowledge on safety, and by maintaining an attitude of trying to identify weaknesses as well as room in the area of safety.</p>	<p>ONR recognises the importance of culture and appropriate leadership for nuclear safety along with the need for learning organisations. A key aspect of ONR’s published mission is that the UK nuclear industry has a culture of continuous improvement and sustained excellence in operations. A key role for ONR is to influence change to create an excellent health, safety and security culture amongst operators, and to promote sustained excellence in nuclear operations.</p> <p>Conclusion IR-2 is also relevant here.</p>

ANNEX K: FUKUSHIMA-1 OPERATOR ACTION SUMMARY

Table K1: Fukushima-1 Operator Action Summary

Time	Reactor Unit 1	Reactor Unit 2	Reactor Unit 3	Reactor Unit 5 and 6 + Ponds
11 March 2011 14.46 earthquake	Loss of AC power ^{§§§§§} SCRAM; DGs start; MSIV isolation Isolation Condenser starts automatically IC manually re-started several times as necessary Suppression chamber cooling spray started manually All operator actions essentially prescribed by procedures in response to Loss of AC power and consequential loss of normal cooling systems	Loss of AC power SCRAM; DGs start; MSIV isolation 14:50 RCIC started manually (following procedures) 14.47 Loss of instrumentation 14:51 RCIC trip (high water level) 15:00 RHR pumps manually started in suppression chamber (S/C) cooling mode 15:02 RCIC started manually 15:28 RCIC trip (high water level) All operator actions essentially prescribed by procedures in response to Loss of AC power and consequential loss of normal cooling systems	Loss of AC power SCRAM; DGs start; MSIV isolation 14:52 SRV cycling 15:05 RCIC started manually 15:25 RCIC trip (high water level) All operator actions essentially prescribed by procedures in response to Loss of AC power and consequential loss of normal cooling systems	Reactor Units 5 and 6 already shutdown EDGs start

§§§§§ For abbreviations see the Section "[Glossary and Abbreviations](#)".

Table K1: Fukushima-1 Operator Action Summary

Time	Reactor Unit 1	Reactor Unit 2	Reactor Unit 3	Reactor Unit 5 and 6 + Ponds
15.37 tsunami	15.37 IC cooling fails (MOVs believed closed prior to tsunami strike; DC power required to open) Worker evacuation	15:36? RHR pumps start shutting down (because of the tsunami) 15:39 RCIC started manually 15:41 (15:37?) SBO + loss of DC power 2 EDGs stop RPV injection continues with turbine driven pump supplying water to the reactor and steam being dumped to S/Cs via spargers - causes temp and pressure increases in PCV	15:38 SBO 16:03 RCIC started manually	EDGs and RHR sea water pumps on Reactor Unit 5 fail 1 EDG on Reactor Unit 6 continued to operate Loss of active cooling to all spent fuel ponds (UP1-6 and common spent fuel pond)
	16:36 TEPCO believe it is impossible to inject water and inability to monitor water level - informs NISA of "inability to inject water"	16:36 TEPCO believe it is impossible to inject water and inability to monitor water level - informs NISA of "inability to inject water"		
	18.18 After 3 hours operators attempt to re-establish IC cooling by opening valve in IC train A			
	20.30 Restoration of MCR lighting	20.30 Restoration of MCR lighting	20:30 RCIC in operation 20:30 Lighting in Central Operating room re-established via temporary supplies	

Table K1: Fukushima-1 Operator Action Summary

Time	Reactor Unit 1	Reactor Unit 2	Reactor Unit 3	Reactor Unit 5 and 6 + Ponds
	21.20 Operators fill IC shell using diesel driven fire pump then open valve in IC train A	22.00 Operators manage to obtain observation of reactor water levels - steady hence infer RCIC operating 22:47 RCIC operation cannot be confirmed due to lack of parameter information		
12 March 2011	00.49 TEPCO suspect PCV pressures may have exceeded maximum - and inform NISA	02:55 RCIC operation verified locally 04.20-05.00 Operators switch water source for RCIC injection from condensate storage tank to S/C (CST depleting; S/C level increasing) - maintains stable reactor water level until 16.34 on 14 March 2011		
	01.48 Injection via IC failure detected (problem with diesel driven fire pump)			
	Sustained high drywell pressures noted			
	05.46 Operators resort to alternative core injection - inject fresh water by fire pumps via the Core Spray lines (SA modification)			06.06 Operators take actions to reduce Reactor Unit 5 RPV pressure
	06.50 Minister orders PCV pressure reduction of Reactor Units 1 and 2	06.50 Minister orders PCV pressure reduction of Reactor Units 1 and 2		

Table K1: Fukushima-1 Operator Action Summary

Time	Reactor Unit 1	Reactor Unit 2	Reactor Unit 3	Reactor Unit 5 and 6 + Ponds
	Preparations for PCV venting commence Fresh water injection by fire pumps via spray line continues			
	09.15-30 Initial attempts for containment wet venting but only partially successful (1 MOV opened 25%)		11:36 RCIC trip (cause unknown but possible battery depletion for valve manipulation) 12:35 HPCI starts automatically (low 2 water level in reactor core)	
	14.00 Additional containment wet venting achieved using temporary air compressor and AC generator to open AOV			
	14.53 Fresh water injection by fire pumps via the Core Spray lines stops - due to exhaustion of fresh water supplies 15:36 Hydrogen explosion (Reactor Unit 1)			
	17.55 Minister orders TEPCO to inject sea-water			
	19.04 Sea-water injection (un-borated) commences using fire fighting lines			
	20.45 Injection of boric acid to prevent return to criticality			

Table K1: Fukushima-1 Operator Action Summary

Time	Reactor Unit 1	Reactor Unit 2	Reactor Unit 3	Reactor Unit 5 and 6 + Ponds
13 March 2011	Sea-water injection essentially continues until 25 th March when change-over to freshwater injection started.	03:00 Drywell pressure increase 0.31MPa 11:00 Containment wet venting configuration carried out - 2 valves opened for venting by connecting an air cylinder to an AOV, and providing AC power to another valve from an engine generator 11:01 Confirmed that S/C side valve chamber was closed and valve inoperable	02:42 HPCI confirmed to have stopped 03:51 Power restored to water level gauge - Low RPV level determined(1/3 core uncovered according to text in IV-73) 04:10/04:15 RPV level judged to have reached top of active fuel (according to Table IV-5-3) 05:10 Due to HPIC stoppage RCIC injection attempted unsuccessfully; operators declare loss of reactor cooling function to NISA 07:39 Primary containment spraying starts 07:45 Readings of reactor water level and pressure 08:41 AOV set "open" for containment wet venting (MOV presumably already opened) by using air cylinders and an engine generator	Water successfully injected into Reactor Units 5 and 6 using condensate transfer pumps powered from operating EDG on Reactor Unit 6

Table K1: Fukushima-1 Operator Action Summary

Time	Reactor Unit 1	Reactor Unit 2	Reactor Unit 3	Reactor Unit 5 and 6 + Ponds
			09:08 Start operation to depressurise the RPV by opening SRV using a car battery and pressure in valve's accumulator; later problems to keep the SRV open (depressurisation to permit water injection to reactor core via alternative systems) 09:20 Detection of decreasing containment pressure 09:25 RPV borated water injection started using fire system lines	Reactor pressure and water level controlled over next few days by opening an SRV and repeatedly refilling the RPV with water from the condensate storage tank (Reactor Units 5 and 6)
			11:17 Containment venting AOV found closed due to loss of air leakage in tank to valves - start to establish connection to engine driven air compressor 12:30 Operation to open AOV to vent from suppression chamber 13:12 Sea water injection with diesel-driven fire pump starts 22:15 Diesel-driven fire pump stopped (before if ran out of fuel)	

Table K1: Fukushima-1 Operator Action Summary

Time	Reactor Unit 1	Reactor Unit 2	Reactor Unit 3	Reactor Unit 5 and 6 + Ponds
14 March 2011			01:10 Sea water injection suspended to as supply of sea-water running low 03:20 Sea water injection resumed 05:20 AOV set to "open" for wet venting - to reduce RPV pressure 11:00 Hydrogen explosion in reactor building 11:25 Reactor pressure and water level readings noted	04.08 Reactor Unit 4 spent fuel pond temperature recorded at 84C
		12:00 High temperature (147C) and pressure (0.48 MPa) in the suppression chamber (S/C) 12:00 Reactor water level decreasing; consequently make preparations for sea water injection		
		13:25 Reactor water level decreasing and possibility that RCIC is inoperable; operator determines a loss of reactor cooling function had occurred (declared to NISA)		
		15:00 Check of RCIC operation state		

Table K1: Fukushima-1 Operator Action Summary

Time	Reactor Unit 1	Reactor Unit 2	Reactor Unit 3	Reactor Unit 5 and 6 + Ponds
		16:00 Operation to open the S/C side valve commences 16:20 Confirmed that S/C side valve is closed 16:34 RPV depressurisation operations start using SRV. Operators use car battery as DC power source and Nitrogen in valves' accumulators - insufficient pressure to open/keep open SRVs Sea water injection operations start using fire pump (insufficient flow to keep core covered suspected?)		
		18:00 RPV pressure decrease observed Later: Problems keeping SRV open; RPV pressure increase 18:22 Fuel believed to be totally uncovered		
		19:22 Sea water injection with fire pump stops because of lack of fuel		
		19:54 Sea water injection into RPV re-starts using fire pump 19:57 Second fire pump for sea water injection into RPV starts		

Table K1: Fukushima-1 Operator Action Summary

Time	Reactor Unit 1	Reactor Unit 2	Reactor Unit 3	Reactor Unit 5 and 6 + Ponds
15 March 2011		06.00 Hydrogen explosion (Reactor Unit 1) Sea-water injection essentially continues until 26 th March when change-over to freshwater injection started.	16:00 AO valve on S/C side found closed 16:05 AO valve on S/C side opened - to re-establish venting	
16 March 2011			01:55 AO valve on S/C side opened Sea water injection continues via fire system until 25 th March - then switched fresh water injection	
17 March 2011				TEPCO attempt to add water to Reactor Unit 3 pond by helicopter drop TEPCO start spraying Reactor Unit 3 pond with water canon from ground
19 March 2011				Temporary sea water pumps provided to RHR systems of both Reactor Unit 5 and 6 permitting both reactors and spent fuel pools to be alternately cooled by switching modes of the RHRs

Table K1: Fukushima-1 Operator Action Summary

Time	Reactor Unit 1	Reactor Unit 2	Reactor Unit 3	Reactor Unit 5 and 6 + Ponds
20 March 2011				Reactor Unit 5 achieves cold shutdown at 14.30; Reactor Unit 6 at 19.27 TEPCO start spraying Reactor Unit 4 pond with water canon from ground Sea-water injection to Reactor Unit 2 pond (method not clear)
22 March 2011				Reactor Unit 4 pond water injection switched to concrete pumping truck (50 tonnes per hour capability)
				Reactor Unit 2 pond cooling switched to spent fuel pool cooling line from 25/3
				Concrete pumping truck used periodically on Reactor Unit 1 pond (from 31/3) and Reactor Unit 3 pond (from 29/3)

All times are stated as Japanese local time.

Table K2: Fukushima-1 Operator Strategy Summary

Reactor Unit 1	Reactor Unit 2	Reactor Unit 3	Reactor Unit 5 and 6 + Ponds
Overall Operator Strategy	Overall Operator Strategy	Overall Operator Strategy	Overall Operator Strategy
<p>Cooling by IC initially Then resort to reactor cooling via alternative water injection into reactor via alternative means (fire fighting lines) - no need to depressurise to permit injection as RPV depressurised (assumed due to damage) PCV pressure reduction (via containment venting) Sea-water injection + Plant status determination Restoration of essential plant information and controls</p>	<p>Cooling initially by RCIC - managing appropriate waters supplies PCV pressure relief Then RPV pressure reduction and sea-water injection on RCIC failure + Plant status determination Restoration of essential plant information and controls</p>	<p>Cooling initially via RCIC Then HPCI cooling following failure of RCIC Then resort to cooling via alternative water injection into reactor via alternative means: <ul style="list-style-type: none"> • Depressurisation to permit alternative injection routes • Via RCIC • Fire system lines Switch to sea-water injection (presumably once fresh water supplies exhausted) + Plant status determination Restoration of some essential plant information</p>	<p><i>For Reactor Units 5 and 6:</i> RPV pressure control Water injection using water from condensate transfer pumps Then switch RHR cooling once sea water pumps connected</p> <p><i>For spent fuel ponds:</i> Water make-up via novel means (progressively more robust) Use of spent fuel cooling line for Reactor Unit 2 fuel storage pond</p>

Table K2: Fukushima-1 Operator Strategy Summary

Reactor Unit 1	Reactor Unit 2	Reactor Unit 3	Reactor Unit 5 and 6 + Ponds
Overall Operator Strategy	Overall Operator Strategy	Overall Operator Strategy	Overall Operator Strategy
<p><i>Key improvisations</i></p> <ul style="list-style-type: none"> • Restoration of lighting from temporary supplies • Use of car batteries to power essential instrumentation and valves • Use of air compressors and AC generators to power essential valves • Sea-water injection • Major restoration of power supplies to site 	<p><i>Key improvisations</i></p> <ul style="list-style-type: none"> • Restoration of lighting from temporary supplies • Use of car batteries to power essential instrumentation and valves • Sea-water injection • Major restoration of power supplies to site 	<p><i>Key improvisations</i></p> <ul style="list-style-type: none"> • Restoration of lighting from temporary supplies • Use of car batteries to power essential instrumentation and valves • Use of air cylinder and engine generator to power essential valves • Sea-water injection • Major restoration of power supplies to site 	<p><i>Key improvisations</i></p> <p>Water make up means for spent fuel ponds (helicopter; water canon; concrete pumping truck)</p>

ANNEX L: PROGRESSION OF THE SEVERE ACCIDENT AT FUKUSHIMA-1 REACTOR UNITS 1, 2 AND 3

- 1 When cooling of the core of a water cooled nuclear reactor is lost, this implies that heat from the decay of fission products is no longer being removed and so the core will eventually start uncovering, overheating and will start degrading. In nuclear reactor terminology, a severe accident is considered to have started from the onset of core damage.
- 2 In the Sections "[Timeline of Key Events](#)" and "[Role and Relevance of Key Reactor Systems During the Fukushima Accident](#)" in the main text, we discussed what we believe to have happened at Fukushima based on available information and actions. However these were either the cause of, or the symptom of, phenomena which were not directly observable (compounded by the loss of instrumentation on some of the reactor units). The nuclear industry has considered severe accident phenomena for many years and, using a combination of past-events, research, fundamental science and computer analysis, is able to make predictions of what can happen during such accidents.
- 3 In the following subsections, we describe the severe accident phenomena that are expected to have happened at the Fukushima-1 Reactor Units 1, 2 and 3 once the core cooling capabilities were lost. We also address other phenomena that could have happened given our current knowledge of Boiling Water Reactor (BWR) severe accidents, although we do not yet have confirmation of occurrence at Fukushima-1.
- 4 Following the discussions on the severe accident phenomena, we then discuss the predictions of computer codes used by the Tokyo Electric Power Company (TEPCO) and Japan's Nuclear and Industrial Safety Agency (NISA) to model these phenomena. Inevitably, there are uncertainties associated with both what we know to have happened and the ability to predict it. In part, this is why the results of two alternative codes are discussed. What the predictions suggest should have happened and what actually occurred at Fukushima should converge with time. As a result of the investigations and research that will be undertaken in the coming years, the nuclear industry's modelling will be updated accordingly for the benefit of the safety of operating and future nuclear power stations. However, for the moment, these computer predictions provide the best information we have on likely progression of the severe accident sequences at the three reactor units.
- 5 The discussions in the following sub-sections are based on evidence from the progression of events as presented in Ref. [2](#); on analyses provided by TEPCO and NISA included in Appendices IV-1 and IV-2 of Ref. [2](#); and on our understanding of the severe accident in BWRs based on Ref. [66](#) and advice from our Technical Support Contractors (TSC) (Refs [26](#) and [27](#)).

Severe Accident Phenomena

Core Damage (Clad Failure, Core Heat-up, Degradation and Relocation)

- 6 Once water injection and other means to cool the reactor (such as the Isolation Condenser in Fukushima-1 Reactor Unit 1) stop, the core cooling capabilities are lost and the reactor core will start overheating, the Safety Relief Valves (SRV) will open, and there will be a continuous loss of inventory from the primary circuit which is not being replenished. The water level in the RPV will drop below the top of the active fuel and will continue decreasing. Eventually, the capability of

transferring heat from the fuel to the coolant will be severely degraded as the fuel will be covered by an increasing fraction of steam rather than liquid water.

- 7 When the temperature reaches 1000°C, the fuel cladding starts failing and the zirconium in the claddings reacts with the steam in the RPV, oxidising and releasing hydrogen. It should be noted that BWRs have relatively large masses of zirconium (in comparison with PWRs of the same size), which implies larger quantities of hydrogen released in this phase of the severe accident progression than for PWRs of the same size. The hydrogen phenomenon is discussed further in a separate sub-section, below.
- 8 The fuel cladding constitutes a barrier between the radioactive material and the environment. As the fuel cladding starts failing the radioactive noble gases, which have abandoned the matrix of the fuel pellet and are accumulated and contained in the tiny space between the fuel cladding and the fuel pellets, will be released.
- 9 When the temperature of the core reaches values above 1400°C, the steel starts melting, which causes the core to start losing its geometry. Different processes between the metallic components occur; melting of the control rod occurs; the degradation continues; and the core starts relocating to the core plate and possibly on to the bottom of the vessel.
- 10 The fuel ceramic uranium dioxide pellet itself is also a barrier between some of the radioactive products of the nuclear fission and the environment, locking in many of the radioactive isotopes produced by fission within its structure. As the degradation of the core continues, those radioactive products which are volatiles and semi-volatiles will be progressively released from the fuel as the temperature increases. Ultimately, if the fuel is allowed to reach temperatures above 2600°C, the ceramic pellets start melting. The heavier fission products that had remained, retained in the interstices of the fuel pellets until that point, can be released.
- 11 Core damage is expected to progress from the top of the core to the bottom. As the molten cladding and steel collapse, the debris causes flow blockages which further hinder the cooling capability of the remaining water in the RPV. However, when the molten core debris relocates into the residual water at the bottom of the vessel, they may be cooled there for a period of time.
- 12 According to Ref. [2](#), the Japanese authorities and TEPCO believe, based on the analyses presented, that core damage and relocation has occurred in the three reactor units. We concur this is a plausible scenario for the three reactor units (Ref. [26](#)), although it is likely to be some time before inspections will be possible to confirm this conclusion. It should be noted that the timings of the above processes will depend on the level of decay heat from the nuclear fuel at the time of loss of cooling; thus, if the reactor core has been cooled for a period of time after the reactor has shutdown, the onset of core damage will be delayed, as predicted for Reactor Units 2 and 3 by both MAAP and MELCOR analyses performed by TEPCO and NISA.

Failure of the Reactor Pressure Vessel

- 13 The Reactor Pressure Vessel (RPV) constitutes another barrier between the radioactive products of the nuclear fission and the environment. Even if the fuel barriers are failed and radioactive materials have been released to the RPV, as long as the integrity of the RPV could be maintained, the radioactive releases to the environment would be minimised.
- 14 BWR RPVs have a large free volume of water below the core. This means that, once the core loses its geometry and relocates to the bottom of the vessel, the debris can be cooled there for a period of time. This phenomenon delays, and could contribute to completely arresting the failure of the

bottom of the vessel (assuming further water can be injected to avoid dry-out). On the other hand, when the molten core debris relocate into the pool of water in the RPV bottom head, and depending on details of the relocation process, steam explosions could occur inside the vessel. The process via which a steam explosion of this type would occur can be broken down into the following four phases (discussed in more detail in Ref. [26](#)):

- Fragmentation and premixing: break up of debris into small particles and mixing into the liquid.
- Triggering: initiation of the steam explosion due to rapid vapour generation
- Propagation.
- Expansion: increase of steam volume and generation of a pressure wave.

This type of scenario is not mentioned in Ref. [2](#), and it should be noted that it has been suggested (Ref. [27](#)) that the structures below the core of BWRs inhibit the possibility of large in-vessel steam explosions. In any case, even if steam explosions had occurred inside any of the three RPVs, we believe that it is unlikely that they would have had sufficient energy to cause RPV failure.

- 15 If RPV dry-out cannot be avoided, the molten core debris is expected to “attack” the vessel wall. Eventually the RPV could fail due to one of, or a combination of, the following mechanisms:
- Failure of penetrations provided for instrumentation.
 - Failure of penetrations provided for the control-rod driving mechanisms.
 - Creep rupture of the vessel.
- 16 From the moment of RPV failure, molten debris is expected to be ejected from the RPV and this is the start of the ex-vessel phenomena. This is discussed in a sub-section below.
- 17 The Japanese authorities have indicated in Ref. [2](#) that there is a possibility that the bottoms of the three RPVs could be damaged. They also indicate that some molten core may have been ejected from the RPVs and have accumulated on the drywell floor.

Ex-vessel Phenomena

- 18 When the molten debris is expelled from the RPV, it will accumulate on the concrete floor of the drywell and may spread towards the steel walls (drywell liner). The molten core debris can still be cooled there by injecting water directly to the drywell, or indirectly into the damaged RPV.
- 19 If the molten core debris cannot be cooled on the drywell floor, two types of challenge to the primary containment can occur: molten core attack to the concrete floor; and molten debris attack to the drywell liner. These are discussed in the following paragraphs.
- 20 Molten core attack to the concrete floor: this phenomenon is generally known as Molten Core Concrete Interaction (MCCI). It can arise when molten core material comes into contact with concrete (in the drywell floor). The phenomenon occurs because of transfer of heat from the molten debris to the concrete. The amount of heat transferred can be affected by the amount and configuration of the molten debris on the drywell floor, as well as by the presence (or not) of water above the molten debris. If the heat transfer to the concrete raises its temperature sufficiently, melting and decomposition of concrete may occur. MCCI has the following potential consequences:

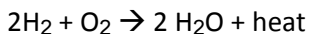
- Generation of non-condensable gases (hydrogen and potentially carbon monoxide or carbon dioxide, depending on the composition of the concrete). Non-condensable gases would contribute to containment pressurisation. In addition, hydrogen and carbon monoxide are combustible gases and may therefore be involved in combustion events
 - Generation of aerosols, including aerosols that may transport radionuclides, which can enhance the radioactive releases.
 - Eventually the MCCI might proceed to a depth sufficient to penetrate the base of the primary containment (base-mat), releasing radioactive material to underground water.
- 21 Molten debris attack to the drywell liner: If the molten material spreads beyond the pedestal region immediately below the reactor vessel, the drywell liner could be attacked. Eventually, liner melt-through could occur. This would defeat the containment pressure-containing capability and could create a path for the release of radioactive material to underground water. For BWRs with a Mark I containment, liner melt-through is generally believed to be unlikely if there is pre-existing water in the containment, but likely if the molten core is released into a dry containment.
- 22 We do not have any evidence that any of these two containment failure mechanisms have occurred or are in progress in any of the Fukushima-1 Reactor Units 1, 2 or 3. Ref. [2](#) mentions these two phenomena on page IV-12 and indicates that the severe accident guidelines contemplate the injection of water into the primary containment to prevent them. However, it does not discuss the possibility of these scenarios in relation to the accidental sequences at Fukushima-1 Reactor Units 1, 2 and 3. MCCI is also considered in a diagram on page IV-137 that shows the possible progression of the accidental sequences and their final outcome. However, this phenomenon appears to be disregarded for the three reactor units due to success of water injection into the primary containment.
- 23 There is a third type of ex-vessel phenomenon that we discuss here for completeness. If the volume in the drywell directly under the RPV had been flooded with water at the time of RPV failure, the molten debris ejected from the bottom of the RPV could have triggered steam explosions as it submerged into the pool of water. This type of scenario is not mentioned in Ref. [2](#). We do not have precise information available regarding the geometry of the three drywells. In addition, given the uncertainty about how much water was injected to the reactors, and whether it all reached its intended target, we are unable to evaluate whether ex-vessel steam explosions would have been possible at all. In any case, even if steam explosions had occurred outside the RPV in any of the three reactor units, we believe that it is unlikely that they would have had sufficient energy to fail the primary containment.

Hydrogen Phenomena

- 24 As mentioned above, hydrogen can be generated during severe accidents in light water reactors due to the reaction between steam and the zirconium present in the fuel cladding. The chemical reaction that occurs is:
- $$\text{Zr} + 2 \text{H}_2\text{O} \rightarrow \text{ZrO}_2 + 2 \text{H}_2 + \text{heat}$$
- The reaction rate is much higher at higher temperatures; for nuclear reactor accidents it can be considered significant for zirconium temperatures above 1000°C.
- 25 The hydrogen produced by the zirconium reactions in the cores at the Fukushima-1 Reactor Units 1 to 3 would have been released to the containment via the SRVs. In small volume containments, such as the Mark I containments at Fukushima-1 Reactor Units 1 to 3, the partial pressure of

hydrogen generated during such an event could, in itself, be a significant contributor to containment pressurisation.

- 26 Hydrogen gas remains stable in an inert atmosphere (such as the nitrogen inerted atmospheres in the Mark I containments at the Fukushima-1 reactor units). However, if a sufficient amount of hydrogen leaks to air, combustion can occur according to the following reaction:



- 27 The above reaction also generates heat, resulting in increasing temperature of surrounding gases. Within an enclosed volume, this temperature increase would imply pressurisation of gases, resulting in pressure loads on structures.
- 28 It is noted that different modes of combustion of hydrogen are possible - diffusion burns, deflagration or detonation. Diffusion burns occur at low hydrogen concentrations only; such burns occur with low flame speeds and the heat can therefore dissipate easily, leading to very low pressure rises. However, deflagration and detonation produce high-speed flames and both modes would be expected to result in beyond capacity loads of structures such as the reactor buildings (secondary containments) at Fukushima-1 Reactor Units 1, 3 and 4. As discussed in the Section [“Role and Relevance of Key Reactor Systems During the Fukushima Accident”](#) in the main text, at Fukushima-1 Reactor Units 1, 3 and 4, hydrogen combustion appeared to have occurred in the reactor buildings (secondary containment), resulting in overpressure and damage of these structures.
- 29 Another process that should be mentioned here for completeness is that over a long period of time, radiolytic decomposition of water could occur which would produce oxygen as well as hydrogen, thereby making combustion inside the primary containment a concern. It is believed that it was primarily for this reason that, in the recovery phase days after the accident, TEPCO’s strategy was to resume the active injection of nitrogen where possible into the primary containments to minimise the risks of further explosions.

Failure of the Primary Containment

- 30 The primary containment (drywell and torus) constitutes the last barrier between the radioactive products of the nuclear fission and the environment. Even if radioactive material has been released from the RPV in the course of the severe accident, as long as the integrity of the primary containment can be maintained, the radioactive releases to the environment can be minimised.
- 31 From the information provided in Ref. [2](#), it appears likely that the primary containments in the three reactor units started leaking via the drywell head flanges and / or the drywell-torus vent bellows when pressures inside reached values above their maximum working pressures. Over-pressurisation would have occurred first due to release of steam via the SRVs into the un-cooled suppression pools. From the onset of core damage, the hydrogen generated would have also contributed to containment pressurisation as discussed above. The sustained high temperature values inside containment could have also been a contributing factor to this failure mechanism for the three containments. In addition, the significant drop of pressure in the Reactor Unit 2 containment at the time when noises were heard near the suppression chamber (currently attributed to a hydrogen explosion) could be due to damage caused by the suspected explosion, or to a breach of the containment due to overpressure.
- 32 The ex-vessel phenomena discussed in a previous sub-section, had they occurred, may have challenged the integrity of the primary containment. As already indicated, we have no evidence or

confirmation that any of these phenomena might have happened at Fukushima-1 Reactor Units 1, 2 and 3.

- 33 The nature of the threat to the integrity of the primary containment can change if the pressure in the RPV is high at the time of vessel failure. In this situation, the failure of the RPV would result in release of the molten core debris at high pressure and, potentially, a phenomenon called Direct Containment Heating (DCH). This may be accompanied by high loads on the structure of the primary containment. DCH is not discussed in Ref. 2 but is considered in a diagram on page IV-137 that shows the possible development of the accidental sequences and their final outcome. However, this phenomenon appears to be disregarded for the three reactor units due to an assumption of successful RPV depressurisation; no further explanation is provided. From the description of the events and the key systems involved in Sections “[Timeline of Key Events](#)” and “[Role and Relevance of Key Reactor Systems During the Fukushima Accident](#)” in the main text, and MELCOR’s predictions shown in Figures 1.1.1, 1.2.1 and 1.3.1 of Attachment IV of Ref. 2, it is not clear that the Reactor Unit 1 RPV was depressurised at the time of vessel failure. On the other hand, we do not have any information leading us to believe that the primary containment in Reactor Unit 1 failed due to this reason.
- 34 Other than the above, we do not know whether other challenges to containment integrity occurred, or are currently occurring, and we do not have precise information regarding the status of the three containments.

Severe Accident Progression

- 35 The interaction of all the phenomena discussed above is complex. Computer models are required to combine the known science and apply it to identified accident sequences. For the time being, the computer models provide the best information on what actually happened within the RPVs and containments at Fukushima. However, they are also important because they are used to model severe accident scenarios in operating and proposed new nuclear power stations to demonstrate that the designs and safety cases are adequate. Going forward, it will be important to reconcile what happened at Fukushima with the computer models to ensure that the uncertainties associated with the accident analyses are reduced, so that the techniques can be used more accurately for the safety analyses of other reactors around the world with the consequential safety benefits to be derived from such analyses and knowledge.
- 36 TEPCO has performed computer-based evaluations of the progression of the severe accident at the three reactor units using the recognised computer code MAAP; these are presented in Attachment IV-1 of Ref. 2. Separate analyses with different assumptions have been undertaken to evaluate the impact of important uncertainties, for example the operation of the Isolation Condenser after the tsunami in Reactor Unit 1, or alternative water injection flows in Reactor Units 2 and 3.
- 37 NISA has undertaken independent severe accident analyses using the code MELCOR, developed by the US NRC; these are presented in Attachment IV-2 of Ref. 2 and include some additional sensitivity analyses and present some additional information on estimated mass of intact fuel and debris. Attachment IV-2 also presents a comparison of the calculated timings with MAAP and MELCOR of the following key events:

- Start of core uncovering
- Onset of core damage
- RPV failure

38 We have assessed the information provided in both Attachments IV-1 and IV-2 of Ref. [2](#) with the help of two of our Technical Support Contractors, who are experienced on BWR severe accident analysis (Refs [26](#) and [27](#)); the main highlights are discussed in the following sub-sections.

39 It should be noted that computer code models for vessel failure cannot be considered to be well validated, due to the lack of an experience base against which to benchmark the codes. It should also be noted that MAAP and MELCOR do not have models for some phenomena discussed above, such as steam explosions. Also, as discussed above, phenomena such as MCCI and DCH appear to have been disregarded in the progression of the severe accident at the three reactor units and have not been evaluated any further. With the limited factual information available at this moment, we do not know whether these phenomena have occurred, i.e. there is no evidence indicating that steam explosions, MCCI and DCH have occurred. Indeed, it is anticipated that new information and new evidence will come to light in the future that will shed more clarity on the real development of the accidental sequences at the three reactor units.

Severe Accident Progression at Fukushima-1 Reactor Unit 1

40 The severe accident analyses for Reactor Unit 1 conducted by TEPCO with the MAAP code are documented on pages 5 to 20 of Attachment IV-1 of Ref. [2](#). The independent analyses for Reactor Unit 1 conducted by NISA with the MELCOR code are documented on pages 1 to 23 of Attachment IV-2 of Ref. [2](#).

41 For this reactor unit, both codes have predicted that core damage and RPV failure to have occurred, but the predicted timings of these events are not consistent.

42 There is approximately one hour's difference between the predictions of both codes in the timings for core uncovering and onset of core damage. This is somewhat surprising since previous benchmark studies have shown both codes to be reasonably consistent in predicting these phenomena. It should be noted however that the plots appear to show very different behaviour of the RPV level early on (Figure 3.1.1 of Attachment IV-1 of Ref. [2](#) for MAAP and Figure 1.1.1 of Attachment IV-2 of Ref. [2](#) for MELCOR) - it appears that the initial level is different in the MAAP and MELCOR analyses (i.e. the calculations may have been based on different initial conditions). It should be borne in mind that we have not had access to the codes input data and boundary conditions assumed, or modelling choices made by the analysts in the calculations with both codes, which might have explained the differences observed. Nevertheless, it seems clear that, if the Isolation Condenser was stopped or not effective after the tsunami, core damage would have started in this reactor unit between three and four hours after the earthquake. The hydrogen explosion that occurred approximately 25 hours after the earthquake is indicative of substantial core damage.

43 The differences between both codes in the predictions of RPV failure timings are much larger but less surprising given the uncertainties associated with this phenomenon and the known differences between both codes. The MAAP analysis predicts the timing of RPV failure at 15 hours after the earthquake, which is very close to the time at which freshwater injection commenced; given this close proximity and uncertainties related to the code predicted timings, it is very difficult to make statements with a high level of confidence about the occurrence or otherwise of vessel failure. It

should be noted, however, that on page IV-45 of Ref. [2](#) it is indicated that there is a significant discrepancy between the large amount of water that had been injected into the Reactor Unit 1 RPV by 31 May 2011, compared to the RPV inventory together with the amount of water that would be lost by steaming; in Ref. [2](#) this is taken to imply that the RPV bottom may be leaking.

- 44 TEPCO's analysis assumes a leak in the primary containment occurring from 18 hours after the earthquake. Under this assumption, MAAP's prediction of the containment pressure matches reasonably the real values measured and recorded.
- 45 TEPCO's analysis and evaluation of plant parameters have led them to believe that the Reactor Unit 1 core is significantly damaged and has relocated to the bottom of the RPV damaging it. They believe, however, that most of the molten debris is being cooled inside the RPV.

Severe Accident Progression at Fukushima-1 Reactor Unit 2

- 46 The severe accident analyses for Reactor Unit 2 conducted by TEPCO with the MAAP code are documented on pages 21 to 41 of Attachment IV-1 of Ref. [2](#). The independent analyses for Reactor Unit 2 conducted by NISA with the MELCOR code are documented on pages 1 to 7 and 24 to 39 of Attachment IV-2 of Ref. [2](#).
- 47 In order to achieve consistency with the recorded RPV level values, the computer analysts assumed in an Analysis Case 1 a sea water injection flow lower than the stated fire pump discharge flow rate (if all the pumped water had reached its intended target, the flow rate should have been sufficient to keep the core covered). The results of the analyses for those conditions are as follows:
- Both codes, MAAP and MELCOR have predicted that core uncover would have started 75 hours after the earthquake, i.e. approximately four hours after the RCIC appeared to have stopped injecting into the RPV.
 - Both codes predict that core damage has occurred in Reactor Unit 2, however the estimated timings are not totally consistent (77 hours after the earthquake according to MAAP results and 80 hours after the earthquake according to MELCOR's).
 - Both codes predict that core damage would have occurred after sea water injection had started approximately 74 hours after the earthquake, indicating that the injection flow would not have been sufficient to flood the core and keep it covered; this is consistent with plant data on RPV water level.
 - Finally, in Analysis Case 1 both MAAP and MELCOR predict that the Reactor Unit 2 RPV would not have failed, indicating that sea water injection would have been sufficient and timely to cool the molten core debris inside the RPV.
- 48 In order to understand the impact of the uncertainty regarding actual sea water injection flow rates, an Analysis Case 2 was conducted assuming a lower sea water flow - in this case both MAAP and MELCOR predict RPV failure in Reactor Unit 2.
- 49 In general, the results of the analyses using MAAP and MELCOR show a reasonable degree of consistency with actual recorded plant data for RPV pressure and level. A much larger discrepancy between the results of one of the MELCOR cases (Figure 2-1-3 of Attachment IV-2, presumed to be a replica of the same case as the first case run by TEPCO with MAAP in Figure 3.2.1.3 of Attachment IV-1) and actual plant data is however shown for containment pressure. This discrepancy is not easy to understand.

- 50 Similar to what was assumed for Reactor Unit 1, TEPCO's analyses for Reactor Unit 2 assume a leak in the primary containment occurring from 21 hours after the earthquake – they believe this assumption is reasonable given that the temperatures had exceeded the design temperature at that time. Under this assumption, MAAP's prediction of the containment pressure matches well the real values measured and recorded up to approximately 70 hours into the sequence.
- 51 Plant values recorded for Reactor Unit 2 show sustained very high pressure in the drywell from the opening of the SRV approximately 74 hours after the earthquake, until noises were heard inside the reactor building near the torus, approximately 87 hours after the earthquake. This long period of sustained high pressure is not predicted by either of the codes. It can be conjectured that the increase of containment pressure at the time of SRV opening, and the sustained high pressure for several hours might have been due to release of non-condensable gases (hydrogen) from the reactor, which would suggest that the degree of core damage at that time would have been higher than that predicted by the results of the calculations. The measured data indicates that failure of the primary containment occurred at approximately the same time as the noises were heard. According to Ref. [2](#), these noises have been tentatively assumed to be due to a possible hydrogen explosion. Whether a hydrogen explosion occurred and damaged the primary containment, or the noises were caused by structural failure of the containment (which was subject to very high pressure for a number of hours) is not yet clear.
- 52 We are unable to explain the significant diversion between the drywell pressure and the pressure in the suppression pool shown by plant records after approximately the time when an SRV was opened, 74 hours after the earthquake.
- 53 TEPCO's Analysis Case 1 concludes that in Reactor Unit 2 the core is partially damaged but the pool of molten debris has not relocated to the bottom of the RPV; therefore, the RPV is not damaged. On the other hand, TEPCO's Analysis Case 2 concludes that the Reactor Unit 2 core is significantly damaged and has relocated to the bottom of the RPV, damaging it. However, based on their evaluation of plant parameters, they believe that, even if the RPV was damaged, most of the molten debris would have remained inside the RPV, where it would be cooled. Given the information available at the time when the calculations were done and the uncertainties, either scenario appears plausible for Fukushima-1 Reactor Unit 2. It should be noted that on page IV-61 of Ref. [2](#) it is indicated that there is a significant discrepancy between the large amount of water that had been injected into Reactor Unit 2 RPV by 31 May 2011, compared to the RPV inventory together with the amount of water that would be lost by steaming; in Ref. [2](#) this is taken to imply that the RPV bottom may be leaking.

Severe Accident Progression at Fukushima-1 Reactor Unit 3

- 54 The severe accident analyses for Reactor Unit 3 conducted by TEPCO with the MAAP code are documented on pages 42 to 66 of Attachment IV-1 of Ref. [2](#). The independent analyses for Reactor Unit 3 conducted by NISA with the MELCOR code are documented on pages 1 to 7 and 40 to 53 of Attachment IV-2 of Ref. [2](#).
- 55 Similar to the modelling approach adopted for Reactor Unit 2, to achieve consistency with the recorded RPV level values, a sea water injection flow lower than the fire pump discharge flow was considered in an Analysis Case 1. The results of the analyses for those conditions are as follows:
- TEPCO's analysis with MAAP has predicted that core uncover would have started 40 hours after the earthquake; NISA's analysis with MELCOR predicts that core uncover would have

started 41 hours after the earthquake, i.e. approximately four to five hours after the High Pressure Coolant Injection (HPCI) stopped injecting into the RPV.

- Both codes have predicted that core damage has occurred in Reactor Unit 3, here again the estimated timings are not totally consistent (42 hours after the earthquake according to MAAP results and 44 hours after the earthquake according to MELCOR's). This is very close or slightly after the time when injection of borated water into the RPV started.
- Finally, in Analysis Case 1, both MAAP and MELCOR predict that the Reactor Unit 3 RPV would not have failed, indicating that water injection would have been sufficient and timely to cool the molten core debris inside the RPV.

56 In order to understand the impact of the uncertainty associated with the actual water injection flow rates, an Analysis Case 2 was conducted assuming a lower water flow - in this case both MAAP and MELCOR predict RPV failure 66 hours and 79 hours after the earthquake, respectively.

57 For this reactor unit, a significant discrepancy can be observed between measured RPV pressure data and RPV pressure values predicted by the codes while the HPCI was injecting water for 14 hours from approximately 22 hours after the earthquake. It was suspected that the drop in RPV pressure could have been due to a steam leak from the HPCI pipework outside the primary containment. When a sensitivity analysis was conducted with MAAP assuming a leak of these characteristics, the code could reproduce the behaviour of the RPV pressure. Having said that, this does not provide evidence that an HPCI leak occurred, although no other plausible explanation has been offered in Ref. [2](#).

58 Some discrepancies are observed between the predicted behaviour of the pressure in the primary containment and the actual values recorded with relation to the number and height of high pressure peaks. However, these can be explained if the actual timings and duration of venting operations had not been accurately recorded and input to the code analyses. Also, both codes appear to predict lower containment pressures than actual plant recorded values while the RCIC was operating; it should be noted that, unlike for Reactor Units 1 and 2, the Reactor Unit 3 analysis did not assume a containment leak.

59 TEPCO's Analysis Case 1 concludes that in Reactor Unit 3 the core is partially damaged but the pool of molten debris has remained retained within the structure of the core and has not reached the bottom of the RPV; therefore, the RPV is not damaged. On the other hand, TEPCO's Analysis Case 2 concludes that the Reactor Unit 3 core is significantly damaged and has relocated to the bottom of the RPV, damaging it. However, based on their evaluation of plant parameters, they believe that, even if the RPV was damaged, most of the molten debris would have remained inside the RPV where it would be cooled. Given the information available at the time when the calculations were done, and the uncertainties, either scenario appears plausible for Fukushima-1 Reactor Unit 3. It should be noted that on page IV-78 of Ref. [2](#) it is indicated that there is a significant discrepancy between the large amount of water that had been injected into the Reactor Unit 3 RPV by 31 May 2011, compared to the RPV inventory together with the amount of water that would be lost by steaming; in Ref. [2](#) this is taken to imply that the RPV bottom may be leaking.

Radioactive Releases

60 The design of the BWRs with Mark I containment have a number of features that have a positive impact in minimising the amount of radioactive releases to the environment as follows:

- Because of the major internal structure above the reactor core, there is a large surface area for fission product deposition. This implies that, in the early stages of the progression of the severe accident, there is significant retention of fission products inside the RPV.
- The suppression pools in Mark I containments store a large amount of water constituting not only a heat sink but also a major contributor to fission product retention. This has been discussed earlier in the Section [“Role and Relevance of Key Reactor Systems During the Fukushima Accident”](#) in the main text.

61 Despite these features, radioactive material has been released to the environment from the three reactor units. The computer codes used NISA (MAAP) and TEPCO (MELCOR) are capable of making predictions of what has been released from each reactor unit. In time, it will be possible to make some limited comparisons of the predictions of the codes with what was actually detected on land in the region around the power station. However, it will not be possible, based on empirical data, to distribute the measured aggregated consequences into the individual reactor units. Only computer modelling allows the radiological consequences from each reactor to be linked to the unique sequence of events that occurred there.

62 The radiological releases from the three Fukushima-1 Units have been briefly discussed in the Section on [“Timeline of Key Events”](#) of the main text. A short summary, covering only a period of a few days after the initial earthquake, based on the severe accident analyses conducted by TEPCO, presented in Attachment IV-I of Ref. 2, is included here for completeness:

- It was estimated that almost all the radioactive noble gases contained in the Unit 1 reactor core were released to the atmosphere during venting operations. Approximately 1% of the content of radioactive caesium iodide (which is the assumed fission product form in the calculations) and less than 1% of other radionuclides were estimated to have been released also, while the remaining inventory was being retained inside the RPV, the drywell and the suppression chamber. Regarding heavy radioactive materials such as plutonium, it was believed that only a very small amount had been released.
- It was estimated that all the radioactive noble gases in the Reactor Unit 2 reactor core were released into the suppression pool and out to the outside via an assumed leak in the primary containment. Approximately 1% of the content of radioactive caesium iodide would have been discharged outside. Most of the remaining inventory would have been retained in the suppression pool.
- It was estimated that approximately 86% (or more, depending on the assumptions in the analysis) of the radioactive noble gases contained in the Reactor Unit 3 reactor core were released to the atmosphere during venting operations. Approximately 0.5% of the content of radioactive caesium iodide would have been discharged outside. Most of the remaining inventory would be retained in the suppression pool.

63 The implications in terms of impact on public health of the radioactive releases to the atmosphere identified above cannot be quantified yet. However, to provide some perspective, we should indicate that the release of a high percentage of radioactive noble gases does not represent a large part of the overall radionuclide inventory of a reactor, and this release (of noble gases) by itself is likely to be of less consequence in terms of human health effects than other radionuclides. Iodine and tellurium, although a much smaller fractional release to the atmosphere, are more important, and in particular they were the main reason for evacuation, sheltering, and distribution of stable iodine tablets. In the longer term, other radionuclides such as caesium may be important because, although the amounts discharged to the atmosphere were lower, the longer half lives mean that they will remain in the environment for much longer.

- 64 As discussed in the Section “[Report of the Japanese Government](#)” in the main text, as a result of the accident and the actions taken to deal with it, significant quantities of radioactivity have escaped into the sea. These actions were unavoidable for cooling the fuel, since the hazard from releases to the atmosphere far outweighs the hazard from marine discharges. Nonetheless, there are mechanisms by which radioactivity in the sea can give rise to radiation exposures of people in Japan and further afield, for example via uptake in seafood. Whilst much is known from routine authorised discharges from nuclear installations, in this respect Fukushima is unlike previous accidents at nuclear sites. In time, more information will become available on the relative importance of the various radionuclides released to the sea, and the environmental pathways that they followed. This information will help to inform planning in terms of immediate and longer term countermeasures as discussed in the Section “[Data Needed to Support Countermeasure Decisions](#)” of the main text.

Final Remarks

- 65 TEPCO and NISA have analysed the severe accident progression at the Fukushima-1 Reactor Units 1, 2 and 3 using the state-of-the-art, internationally recognised, codes MAAP and MELCOR. Over time, more information is expected to become available on what the final state of the reactor cores and vessels are, but for now the severe accident analyses documented in Ref. [2](#) provide valuable insights into the possible progression of the accidental sequences at the three reactor units.
- 66 The assumptions made in the various analysis cases are clearly stated and, in broad terms, they appear to be reasonable, although detailed review of the analyses, including the input data, boundary conditions assumed and modelling choices, would also be helpful in view of some of the aspects that are difficult to understand, as discussed in the previous sub-sections.
- 67 Given the information and time available to conduct and document the analyses presented in Attachments IV-1 and IV-2 of Ref. [2](#), it is understandable that only a limited set of sensitivity analyses have been conducted to address key areas of uncertainty. One of the most significant assumptions, the delivered RPV injection flow, is included in the sensitivity analyses and shows the importance of this parameter.
- 68 Finally, sufficient analysis results have been provided in Ref. [2](#) for us to be able to understand the analyses and the conclusions, again with the caveat that there are some aspects of the inputs and modelling for which, ideally, it would be useful to have more information in order to enhance our understanding further.

REFERENCES

- 1 *Japanese earthquake and tsunami: Implications for the UK nuclear industry. Interim Report* ONR Report ONR-FR-REP-001 Revision 3 HM Chief Inspector of Nuclear Installations 18 May 2011 www.hse.gov.uk/nuclear/fukushima/interim-report.pdf
- 2 *Report of the Japanese Government to the IAEA Ministerial Conference on Nuclear Safety – The Accident at TEPCO’s Fukushima Nuclear Power Stations* Nuclear Emergency Response Headquarters Government of Japan June 2011 www.iaea.org/newscenter/focus/fukushima/japan-report/
- 3 *Mission report* IAEA International Fact Finding Expert Mission of the Fukushima Dai-ichi NPP Accident Following the Great East Japan Earthquake and Tsunami Tokyo, Fukushima Dai-ichi NPP, Fukushima Dai-ni NPP and Tokai Dai-ni NPP, Japan 24 May–2 June 2011.
- 4 *Reducing risks, protecting people: HSE’s decision-making process* HSE Books 2001 ISBN 0 7176 2151 0 www.hse.gov.uk/risk/theory/r2p2.pdf
- 5 *Safety assessment principles for nuclear facilities* 2006 edition (Revision 1) HSE January 2008 www.hse.gov.uk/nuclear/saps/saps2006.pdf
- 6 *VGB Power Tech earthquake and tsunami in Japan and consequences for Fukushima and other nuclear power plants* www.vgb.org/en/tohoku.html
- 7 *Preliminary Summary* IAEA International Fact Finding Expert Mission of the Fukushima Dai-ichi NPP Accident Following the Great East Japan Earthquake and Tsunami Tokyo, Fukushima Dai-ichi NPP, Fukushima Dai-ni NPP and Tokai Dai-ni NPP, Japan 24 May - 2 June 2011 www.iaea.org/newscenter/focus/fukushima/missionsummary010611.pdf
- 8 *Boiling Water Reactor – GE BWR/4 – Technology Advanced Manual – Chapter 6.0 – BWR Differences* United States Nuclear Regulatory Commission Date unknown pbadupws.nrc.gov/docs/ML0230/ML023010606.pdf
- 9 *Reactor Concepts Manual – Boiling Water Reactor Systems* USNRC Technical Training Centre United States Nuclear Regulatory Commission Date unknown <http://www.nrc.gov/reading-rm/basic-ref/teachers/03.pdf>
- 10 *Nuclear tourist website* www.nucleartourist.com
- 11 Okimoto D, Hanson A, Marvel K *The nuclear crisis in Japan* 21 March 2011 iis-db.stanford.edu/evnts/6615/March21_JapanSeminar.pdf
- 12 Kumano Yumiko, Tokyo Electric Power Company ‘Integrity inspection of dry storage casks and spent fuel at Fukushima Dai-ichi Nuclear Power Station’ ISSF 2010 presentation 16 November 2010
- 13 *Japanese earthquake and tsunami: Implications for the UK military and defence facilities – DNSR Assessment* Ministry of Defence Defence Nuclear Safety Regulator DNSR/6/6/1[1151] 22 July 2011
- 14 *Report of the IRRS mission to UK in April 2006* IAEA www.hse.gov.uk/nuclear/regulatoryreview/irrsreducedscope.pdf
- 15 *Report of the second IRRS mission to UK in October 2009* IAEA www.hse.gov.uk/nuclear/regulatoryreview/irrs-report.pdf

- 16 *The record of the earthquake intensity observed at Fukushima Dai-ichi Nuclear Power Station and Fukushima Power Station (Interim Report)* TEPCO press release 1 April 2011
www.tepco.co.jp/en/press/corp-com/release/index-e.html
- 17 Brady, A Gerald (1980) and Ellingwood, Bruce (ed.) *An investigation of the Miyagi-ken-oki, Japan, earthquake of June 12, 1978* NBS special publication 592 United States Department of Commerce, National Bureau of Standards http://www.nist.gov/manuscript-publication-search.cfm?pub_id=908930
- 18 *Results of the investigation regarding tsunami arrived in Fukushima Dai-ichi Nuclear Power Station and Fukushima Power Station* TEPCO press release 9 April 2011
<http://www.tepco.co.jp/en/press/corp-com/release/11040910-e.html>
- 19 *Situation Report 135* Japanese Fire Department
- 20 *Fukushima nuclear accident update* IAEA 24 March 2011 14:00 UTC
www.iaea.org/newscenter/focus/fukushima/
- 21 *Plant status of Fukushima Dai-ichi Nuclear Power Station (as of 3:00pm, June 29)* TEPCO press release 29 June 2011
- 22 *Plant status of Fukushima Dai-ichi Nuclear Power Station (as of 3:00pm, July 15)* TEPCO press release 15 July 2011
- 23 *Seismic damage information* (80th release) NISA briefing 8 April 2011 www.nisa.meti.go.jp/english/
- 24 *Seismic damage information* (40th release) NISA briefing 21 March 2011
www.nisa.meti.go.jp/english/
- 25 Fujimoto H, Kondo K, Ito T, Kasagawa Y, Kawabata O, Ogino M, Yamashita M *Circumstances and present situation of accident management implementation in Japan* OECD/NEA workshop on Implementation of severe accident management measures (ISAMM–2009) JNES October 2009 (Note: This reference should be used in conjunction with the actual slides presented during the workshop
sacre.web.psi.ch/ISAMM2009/ISAMM09/Presentations/Session%201%2838,9,6,8,33%29/Paper%201.4%288%29Fujimoto.pdf)
- 26 *Fukushima Accident Sequence Review* JEL-HSE-1101 Revision 1 September 2011
- 27 *Fukushima Accident Analysis Review* ERIN Letter to ONR No P0636110001-4020 August 2011
- 28 *Station blackout at Browns Ferry Unit 1 – Accident Sequence Analysis* NUREG/CR-2182 United States Nuclear Regulatory Commission November 1981
www.ornl.gov/info/reports/1981/3445600211884.pdf [3.7MB]
- 29 *Response to the Office of Nuclear Regulation’s ‘Invitation to submit information on the implications of the Fukushima nuclear accident’* Jacobsen Engineering Limited June 2011
- 30 *Installation of a hardened wetwell vent* Generic letter 89–16 United States Nuclear Regulatory Commission September 1989 www.nrc.gov/reading-rm/doc-collections/gen-comm/gen-letters/1989/gl89016.html
- 31 *Technical guidelines for seismic design of nuclear power plants* JEAG 4601–2002
- 32 United States Nuclear Regulatory Commission *Regulatory guide for reviewing nuclear reactor site evaluation and application criteria* NSCRG: L-ST-I.0 May 1964

- 33 *Regulatory guide for reviewing seismic design of nuclear power reactor facilities decision of Atomic Energy Commission September 1978* Revised by Nuclear Safety Commission on 20 July 1981 Revised by Nuclear Safety Commission on 19 September 2006
www.fujipress.jp/JDR/open/newguideline_e.pdf
- 34 *Convention on nuclear safety. National Report of Japan for the Fourth Review Meeting September 2007*
www.nisa.meti.go.jp/english/internationalcooperation/conventions/cns/pdf/4th_NationalReport.pdf [4.56MB]
- 35 *Tsunami assessment method for nuclear power plants in Japan* Tsunami Evaluation Subcommittee JSCE 2002 committees.jsce.or.jp/ceofnp/system/files/JSCE_Tsunami_060519.pdf
- 36 'The 869 Jogan tsunami deposit and recurrence interval of large scale tsunami on the Pacific coast of northeast Japan' *Journal of Natural Disaster Science* 2001 **23** (2) 83–88
- 37 *The threat posed by tsunami to the UK* Defra 2005
archive.defra.gov.uk/environment/flooding/documents/risk/tsunami05.pdf
- 38 *Level 2 PSA methodology and severe accident management* OECD/GD(97)198
[www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=OCDE/GD\(97\)198&docLanguage=En](http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=OCDE/GD(97)198&docLanguage=En) [1.16MB]
- 39 Nuclear Emergency Planning and Liaison Group, Department of Energy and Climate Change *Consolidated Guidance*
www.decc.gov.uk/en/content/cms/meeting_energy/nuclear/safety_and_sec/emergency_plan/nep_lg/guidance/guidance.aspx
- 40 *Japanese earthquake and tsunami: Implications for the nuclear industry* EDF Energy 17 June 2011
- 41 *Japanese earthquake and tsunami: Implications for the nuclear industry* EDF Energy 27 July 2011
- 42 *Japanese earthquake and tsunami: Implications for the nuclear industry. Interim Report* Magnox Oldbury Technical Centre Ref: MXN32024/N 16 June 2011
- 43 *Japanese earthquake and tsunami: implications for the nuclear Industry. Interim Report* Magnox Oldbury Site Ref: MXN32024/N 29 July 2011
- 44 *Response to the Interim Report on the Japanese earthquake and tsunami* Horizon Nuclear Power Ref: HNP20039N 14 June 2011
- 45 *Update on Horizon Nuclear Power response to recommendations of the Interim Report* Horizon Nuclear Power Letter No HNP20042N 28 July 2011
- 46 *Response to recommendations contained within ONR report – Japanese earthquake and tsunami: Implications for the UK nuclear industry* NuGen 16 June 2011
- 47 *July update on our response to recommendations contained within ONR report – Japanese earthquake and tsunami: Implications for the UK nuclear industry* NuGen 29 July 2011
- 48 *Response to Recommendations in ONR Interim Report on Fukushima Events* EDF and AREVA Letter No ND(NII) EPR00879N 17 June 2011
- 49 *ONR Interim Report - Japanese Earthquake and Tsunami Implications to the UK Nuclear Industry* Westinghouse Electric Company LLC Letter No WEC00609N 15 June 2011
- 50 *Sellafield Limited Response to: Japanese earthquake and tsunami: Implications for the UK Nuclear Industry – Interim Report* Sellafield Limited Letter No ONR/11/10351/02 15 June 2011

- 51 *Sellafield Limited Progress Report on 26 recommendations from: Japanese earthquake and tsunami: Implications for the UK Nuclear Industry – Interim Report* Sellafield Limited Letter No ONR/11/10351/03 27 July 2011
- 52 *Response to the ONR Interim Report – Japanese earthquake and tsunami: implications for the UK nuclear Industry* Dounreay Site Restoration Limited DNSC(11)P12 Issue 2 17 June 2011
- 53 *Update to ONR on the 8 actions identified by DSRL from review of the ONR Interim Report on the Japanese earthquake and tsunami* Dounreay Site Restoration Limited ENG/ASSR(11)P019 Issue 1 28 July 2011
- 54 *Response to Recommendation 26 of the Japanese earthquake and tsunami: Implications for the UK nuclear industry* RSRL RSRL/ONR/00025N 17 June 2011
- 55 *Responses to ONR recommendations in HM Chief Inspector’s interim Fukushima report* URENCO UK Limited ONR/2011/28N 16 June 2011
- 56 *Fukushima Incident – Responses from Springfields Fuels Limited to Chief Inspector’s Interim Report Recommendations* Springfields Fuels Limited TOONR 2/11 9 June 2011
- 57 *Response to interim report* LLW Repository Limited LLWR/NII/11/0093-03 21 June 2011
- 58 *Response to Interim Report: Japanese earthquake and tsunami.* Studsvik UK Limited 17 June 2011
- 59 *Response to Interim Report: Japanese Earthquake and tsunami; implications for the UK nuclear Industry* Imperial College ICRC/ONR-Safety/2011/2 17 June 2011
- 60 *Response to Interim Report* GE Healthcare Limited 17 June 2011
- 61 *AWE response to the Japanese earthquake and tsunami: Implications for the UK nuclear industry – interim report* AWE AWE/MD/29/11 17 June 2011
- 62 *Rolls Royce Marine Power Operations (RRMPOL) reply to the recommendations in the Fukushima interim report* Rolls Royce Marine Power Operations 16 June 2011
- 63 *BAE Systems Marine Limited Response to the recommendations of the Fukushima interim report* BAE Systems Marine Limited 16 June 2011
- 64 *DRDL Response to ONR Interim Report* Devonport Royal Dockyard Limited CE-(ss)-11 17 June 2011
- 65 *Response to the Recommendations arising from the Chief Inspector’s Interim Report on the Implications of events at Fukushima for the UK Nuclear Industry* Rosyth Royal Dockyard Limited 251/43/2/2 16 June 2011
- 66 Leonard Mark T, dycoda LLC L2-5: *Sample calculation of severe accident progression* Presented at a course sponsored by IAEA in Beijing, China May 2011
- 67 *Convention on nuclear safety* INFCIRC/449 1994 IAEA
www.iaea.org/Publications/Documents/Infcircs/Others/inf449.shtml
- 68 *Development and Flood Risk Planning Policy Statement* 25 PPS25 March 2010
- 69 *Report by HM Nuclear Installations Inspectorate on the Results of Magnox Long Term Safety Reviews (LTSRs) and Periodic Safety Reviews (PSRs)* www.hse.gov.uk/nuclear/magnox.pdf
- 70 *Magnox nuclear power reactor programme: NII’s report on the outcome of the programme of generic safety issues*

While every effort has been made to ensure the accuracy of the references listed in this report, their future availability cannot be guaranteed.

GLOSSARY AND ABBREVIATIONS

AC	Alternating Current
Accropodes	Man-made unreinforced concrete objects designed to resist the action of waves on breakwaters and coastal structures.
ACR	Atriculated Control Rods
ADS	Automatic Depressurisation System
AEC	Atomic Energy Commission (Japan)
AETP	Active Effluent Treatment Plant
AGR	Advanced Gas-cooled Reactor
AIC	Alternative Indication Centre
ALARP	As Low As Reasonably Practicable
AOD (level)	AOD - Above Ordinance Datum - The level relative to the ordinance datum at Newlyn. Tidal levels are quoted relative to chart datum (approximately the lowest level due to astronomical effects and excluding meteorological effects). The chart datum varies with location and is between 0 and 7m from ordinance datum at Newlyn.
AOV	Air Operated Valve
AREVA	AREVA NP SAS
ASN	Autorité de Sûreté Nucléaire (French nuclear safety authority)
AWE	Atomic Weapons Establishment
AWV	Active Waste Vaults
BAESM	BAE Systems Marine Limited
Berm	An artificially placed continuous ridge or bank of earth or stones.
BSL	Basic Safety Limit (in ONR SAPs)
BSO	Basic Safety Objective (in ONR SAPs)
BWR	Boling Water Reactor
C&I	Control and Instrumentation
CACS	Circulator Auxiliary Cooling System
CCA	Civil Contingencies Act 2004
CCS	Containment Cooling System
CFIL	Council Food Intervention Level
Cliff-edge	A cliff-edge effect is a small change in a parameter that leads to a disproportionate increase in consequences.
Climate Change	Long-term variations in global temperatures and weather patterns, both natural and as a result of human activity.

Climate Change Scenario	A coherent and internally consistent description of the change in climate by a certain time in the future, using a specific modelling technique and under specific assumptions about the growth of greenhouse gas and other emissions and about other factors that may influence climate in the future.
CNS	Convention on Nuclear Safety
COBR	Cabinet Office Briefing Room
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.
CRCE	Health Protection Agency Centre for Radiation Chemical and Environmental Hazards (formerly the NRPB)
CS	Core Spray
CST	Condensate Storage Tank
CW	Cooling Water
DBA	Design Basis Analysis
DBE	Design Basis Earthquake
DBF	Design Basis Flood
DC	Direct Current
DCH	Direct Containment Heating
DCP	Dounreay Cementation Plant
DECC	Department of Energy and Climate Change
Defra	Department for Environment, Food and Rural Affairs
DEPZ	Detailed Emergency Planning Zone
DfT	Department for Transport
DFR	Dounreay Fast Reactor
DG	Diesel Generator
DMTR	Dounreay Materials Test Reactor
DNSR	Defence Nuclear Safety Regulator
DRDL	Dounreay site Restoration Limited
DSRL	Dounreay Site Restoration Limited
DoH	Department of Health
DTM	Digital Terrain Model
DWP	Department for Work and Pensions
ECC	Emergency Control Centre
ECCS	Emergency Core Cooling System
EDF	Electricité de France SA
EDG	Emergency Diesel Generator
ENSREG	The European Nuclear Safety Regulatory Group
EPREV	Emergency Preparedness Review

EOP	Emergency Operating Procedures
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.
ERL	Emergency Reference Level
EU	European Union
FCA	Fuel Cycle Area
FCERM	Food and Coastal Erosion Risk Management
FCO	Foreign and Commonwealth Office
FCS	Flammability Control System
Flood Zone	A geographic area within which the flood risk is in a particular range, as defined within PPS25 (Ref. 68).
FSA	Food Standards Agency
Gabion	A large compartmentalized container, usually cylindrical or rectangular, often fabricated from galvanized steel wire mesh. When filled with stone it is used in the construction of foundations, dams, erosion breaks and retaining walls.
GDA	Generic Design Assessment
GE	General Electric
GEHC	GE Healthcare Limited
GT	Gas Turbine
HAT	Highest Astronomical Tide
HIRE	Hazard Identification and Risk Evaluation
HPA	Health Protection Agency
HPCI	High Pressure Coolant Injection
HRO	High Reliability Organisations
HSE	Health and Safety Executive
HSWA74	Health and Safety at Work etc. Act 1974
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ILW	Intermediate Level Waste
INES	International Nuclear and Radiological Nuclear Event Scale
INSAG	International Nuclear Safety Advisory Group
IRR99	Ionising Radiation Regulations 1999
IRRS	Integrated Regulatory Review Service
ISSC	International Seismic Safety Centre
JNES	Joint Convention on Nuclear Safety
JNES	Japan Nuclear Energy Safety Organisation
kV	Kilovolts

LAT	Lowest Astronomical Tide
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.
LLW	Low Level Waste
LLWR	Low Level Waste Repository <i>or</i> LLW Repository Limited
LBLOCA	Large-break Loss of Coolant Accident
LOCA	Loss of Coolant Accident
LOOP	Loss of Off-site Power
LPCI	Low Pressure Coolant Injection
LTSR	Long Term Safety Review
LWR	Light Water Reactor
MAAP	Modular Accident Analysis Program is a computer code that simulates the response of light water and heavy water moderated nuclear power plants during severe accident sequences.
Magnitude	The earthquake magnitudes referred to in this report are M_w , Moment Magnitude.
MCCI	Molten Core Concrete Interaction
MDEP	Multi-national Design Evaluation Programme
MELCOR	MELCOR is a fully integrated, engineering-level computer code whose primary purpose is to model the progression of accidents in light water reactor nuclear power plants.
METI	Ministry of Economy, Trade and Industry (Japan)
MEXT	Ministry of Education Culture Sport Science and Technology (Japan)
MHWS	Mean High Water Springs
M_L	Local Magnitude
MLWS	Mean Low Water Springs
MoD	Ministry of Defence
MOV	Motor Operated Valve
MOX	Mixed Oxide
MUWC	Make-up Water Condensate Cooling System
NDA	Nuclear Decommissioning Authority
NEA	Nuclear Energy Agency (of the OECD)
NEBR	Nuclear Emergency Briefing Room
NEPLG	Nuclear Emergency Planning Liaison Group
NIA65	Nuclear Installations Act 1965, as amended
NISA	Nuclear and Industrial Safety Agency (Japanese nuclear safety regulator)
NNB	Nuclear New Build
NNPP	Naval Nuclear Propulsion Programme
NPP	Nuclear Power Plant

NRPB	National Radiological Protection Board (now HPA-CRCE)
NRI	Nuclear Research Index
NSC	Nuclear Safety Commission (Japan)
Nuclear safety	The achievement of proper operating conditions, prevention of accidents or mitigation of accident consequences, resulting in protection of workers, the public and the environment from undue radiation hazards.
NuGen	NuGeneration Limited
OECC	On-site Emergency Control Centre
OECD	Organisation for Economic Co-operation and Development
ONR	Office for Nuclear Regulation (formerly the Nuclear Directorate of the HSE)
OP (level)	In Japan, tidal levels are quoted relative to a fixed level, similar to AOD in the UK. The datum is the Onahama Port Base level.
OSP	Operational Safety Program
Pa	Per Annum
PCV	Pressure Containment Vessel
PFR	Prototype Fast Reactor
Pga	Peek Horizontal Ground Acceleration
POSRV	Pilot Operated Safety Relief Valve
PSA	Probabilistic Safety Analysis
PSR	Periodic Safety Review
PSR1	The first Periodic Safety Review
PSR2	The second Periodic Safety Review
PVCW	Pressure Vessel Cooling Water
PWR	Pressurised Water Reactor
RCCA	Rod Cluster Control Assemblies
RCIC	Reactor Core Isolation Cooling
RCS	Reactor Coolant System
REPPIR	Radiation (Emergency Preparedness and Public Information) Regulations 2001
RHR	Residual Heat Removal
RPV	Reactor Pressure Vessel
RRDL	Rosyth Royal Dockyard Limited
RRMPOL	Rolls Royce Marine Power Operations Limited
RSRL	Research Sites Restoration Limited
Run-up	The run-up is the rush of water up a beach or structure on the breaking of a wave. The height of the run-up is the vertical height above the still water level that the rush of water reaches.
SAG	Severe Accident Guidelines
SAGE	Scientific Advisor Group for Emergencies

SAM	Severe Accident Management
SAMG	Severe Accident Management Guidelines
SAP	Safety Assessment Principle(s) (ONR)
SBERG	Symptom Based Emergency Response Guidelines
SBO	Station Blackout
SCC	Strategic Coordinating Centre
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. 31).
SDF	Safety Directors' Forum
SEPA	Scottish Environment Protection Agency
SFAIRP	So Far As Is Reasonably Practicable
SFL	Springfields Fuels Limited
SGHWR`	Steam Generating Heavy Water Reactor
SHC	Reactor Shutdown Cooling System
SMP	Sellafield MoX Plant
SNUPPS	Standardised Nuclear Unit Power Plant System
SOI	Station Operating Instruction(s)
SoS	Secretary of State
SPEEDI	System for Prediction of Environment Emergency Dose Information
SQEP	Suitably Qualified and Experienced Personnel
SRV	Safety Relief Valve
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. 31).
SSA	Strategic Siting Assessment
STAC	Scientific and Technical Advice Cell
SV	Safety Valve
Syzygy	A straight line configuration of three celestial bodies (such as the Earth, Sun, and Moon) in a gravitational system.
TAG	Technical Assessment Guide(s) (ONR)
TAP	Technical Advisory Panel
TEPCO	The Tokyo Electric Power Company
TIG	Technical Inspection Guide(s) (ONR)
TSC	Technical Support Contractor
UKCIP	UK Climate Impacts Programme
US NRC	Nuclear Regulatory Commission (United States of America)
UUK	URENCO UK Limited

WAGR Windscale Advanced Gas-cooled Reactor
WENRA Western European Nuclear Regulators' Association

CONTACTS

HM Chief Inspector of Nuclear Installations
Office for Nuclear Regulation
Redgrave Court
Merton Road
Bootle
Merseyside
L20 7HS

www.hse.gov.uk

email: fukushimaONRRReport@hse.gsi.gov.uk

For information about health and safety visit www.hse.gov.uk. You can view HSE guidance online and order priced publications from the website. HSE priced publications are also available from bookshops.

This document is issued by the Office for Nuclear Regulation (ONR), an agency of HSE. For further information about ONR, or to report inconsistencies or inaccuracies in this publication please visit www.hse.gov.uk/nuclear.

ONR-FR-REP-11-002 Revision 2

2011/506508