Small Modular Reactor Techno-Economic Assessment

Project 4

Final Report

Volume I

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This is Volume I of a two-volume report.

In Volume II is presented a detailed assessment of various SMR designs, in particular with reference to the issues raised in the GDA of current large plant. This is informed by material provided under Non Disclosure Agreements, and is commercially confidential, and must not be disclosed.

In Volume I we draw on the detailed assessments of Volume II to present a generic assessment of the licensing and permitting issues likely to arise in GDA of an SMR.

EXECUTIVE SUMMARY

It is expected that licensing and permitting process for an SMR being introduced into the UK would involve a Generic Design Assessment (GDA) by the Office for Nuclear Regulation (ONR) and the Environment Agency (EA) and/or Natural Resources Wales (NRW). To identify issues likely to arise in a GDA process, a pre-GDA assessment of SMR designs was undertaken as part of the SMR Techno-Economic Assessment (TEA) process. The aim of the assessment was to identify issues and challenges that could arise and also to develop possible arguments by which they might be addressed.

To perform the assessment, published UK regulatory principles were reviewed to identify UK regulatory expectations judged likely to significantly impact licensing and permitting of an SMR design. Previously published GDA assessments for large reactors were also reviewed to identify significant issues raised that could also apply to the SMRs. The list of potentially significant issues was validated at workshops and meetings held with the regulators themselves. The applicability of the issues to the proposed SMR designs were then analysed and recommendations made on how they might be addressed.

The main findings of the assessment were as follows:

- Specific UK requirements for the design of systems protecting a reactor against faults and hazards may result in significant changes to current SMRs designs, potentially with a large economic impact on a cost-per-megawatt basis. Should a requirement for a plant design change be indicated to meet UK principles, it is recommended that the SMR vendor perform a cost-benefit analysis using state-of-the–art probabilistic techniques, to justify that the risk benefit achieved was large enough to justify the cost and difficulty of the plant modification. Such an analysis could be used as a basis for a discussion with the UK regulators on whether the modification would be justified against the UK requirement of ALARP. (See Section 3.3.1)
- Specific UK requirements for inspection of 'high integrity components' such as the Reactor Pressure Vessel, could have a significant economic impact on an SMR programme due to the potentially high cost-per-megawatt of initial and recurring inspections. Additionally, necessary in-service inspections may be more difficult due to the compact designs of some SMRs, which may not allow access for inspection by current techniques. It is recommended that at an early stage of GDA an SMR developer should identify the components and welds that are to be classified as high integrity components, together with the inspection method that will be applied, taking account of access constraints. It is further recommended that to facilitate a UK SMR programme, consideration should be given to initiating a significant research programme in the non-destructive examination area, capitalizing on the existing UK expertise, and aimed at improving the ability to detect defects in complex geometries, and developing "condition monitoring" techniques for semi-continuous and remote assessment of components. (See Section 3.3.11)
- UK requirements for the design, testing and application of software-based, instrumentation and control systems for nuclear safety purposes are considered likely to result in significant changes being required to the control and instrumentation systems proposed for many of the SMRs. To assist in the regulatory acceptance of the software based control and instrumentation systems in SMRs it is recommended that research is initiated in software specification, design and testing, with the aim of raising the general level of confidence in the use of software in safety critical systems in nuclear applications. Further research is also recommended to help understand the way in which software is used in safety critical applications outside the nuclear sector, along with an assessment of how such usage could be mapped across into the nuclear sphere. (See Section 3.3.14)
- A GDA of a plant design requires a comprehensive safety and environmental submission, linked to a 'frozen' reference design for plant items that are important to nuclear safety. Lack of a properly defined reference design that was clearly linked to the safety and environmental case was considered by the regulators to have been a significant impediment to completion of previous GDAs. To minimise delays in GDA

acceptance it is recommended that that need for a frozen reference design linked to a safety and environment case, is identified to an SMR vendor as early as possible in the GDA process. (See Section 3.3.21)

- Many SMR designs rely on "passive" natural circulation cooling for heat removal in faults or in normal operation. Developing computational tools to predict natural circulation behaviour is in principle possible, but it is very much at the frontier of current research in nuclear thermal hydraulics, especially for conditions where local boiling is taking place. To help inform regulatory assessments of SMR safety submissions, it is recommended that a UK research programme is initiated to conduct tests on suitably scaled measurement facilities, and develop and validate predictive methods for natural circulation. (See Section 3.3.26)

Volume II of the current report provides a fuller description of the methodology followed for the current assessment: it contains material provided by SMR vendors under non-disclosure agreements, and is thus commercially confidential.

1 INTRODUCTION

An initial HMG SMR feasibility study [1] considered that it was likely that an SMR planned for introduction into the UK would be likely to undergo a Generic Design Assessment (GDA), similar to that used for previous UK new-build reactors. Ref [1] considered that it would be helpful to undertake a pre-GDA study at an early stage, to provide an early identification of generic licensing issues of most significance for SMRs and develop potential arguments by which they might be addressed. DECC therefore commissioned a pre-GDA study of candidate SMR technologies with the following objectives:

- To perform an initial identification of the generic issues that would be likely to affect the licensing of SMRs in the UK and develop possible generic safety and environmental arguments that might be used to address them in order to facilitate regulatory acceptance.
- To organise a Workshop with the UK safety and environmental regulators to confirm and validate the list of generic licensing issues.

The issues were to include the following, identified in the feasibility study[1]:

- The challenges of operating a nuclear licensed site containing multiple reactor modules.
- The human factors challenges associated with reduced manning levels, and the challenges associated with the use of passive safety systems in SMRs.
- The specific safeguard vulnerabilities of SMR designs.
- The challenges associated with the use of programmable Control and Instrumentation (C&I) systems in SMRs.
- The challenges associated with high reliability claims in the Probabilistic Safety Assessments for some SMRs.

The issues identified, and the safety claims and arguments proposed to address them, would be informed by lessons learnt from recent experience from the GDAs of large reactors.

The current report presents the results of the pre-GDA study.

Volume I, this present document, presents the results of the generic study referred to above and the generic conclusions that were reached.

Volume II provides a fuller description of the methodology followed, lists the main reference documentation used, and presents an assessment of the individual designs submitted by vendors against UK requirements, informed by experience of the GDA of large reactors. Volume II contains material provided by SMR vendors under non-disclosure agreements, and is thus commercially confidential, and must not be disclosed.

In Section 2 we summarise the approach adopted (and which is presented in more detail in Volume II). In Section 3 we review issues identified as important to SMR regulatory acceptance, with reference to generic types of SMR, identifying possible responses to these to aid the licensing. In Section 4 we discuss these issues, summarise these responses, and make generic recommendations. Conclusions are drawn in Section 5.

2 THE APPROACH ADOPTED FOR THE "PRE-GDA" ASSESSMENT

GDA is the first phase of a two-part process that has been applied to new-build designs in the UK. GDA involves an in-depth review by ONR and the Environmental Regulators of a safety, security and environmental report (SSER) for a proposed new reactor design, submitted by a Requesting Party (RP). GDA concentrates on generic aspects of the design and does not consider features of any specific site: instead a generic site is postulated which reasonably envelopes the characteristics of real UK sites. GDA is concluded by the issuing of a Design Acceptance Confirmation (DAC) by ONR and a Statement of Design Acceptability (SoDA) by EA. The GDA is followed by a site-licensing phase, which is a statutory phase in which site-specific elements of the safety, security and environmental report and applications for Operational Environmental Permits are submitted to the regulatory authorities for approval.

GDA has been completed for the UK EPR reactor and is at an advanced stage for the AP1000 design. GDA for the UK ABWR design began in 2014. The GDAs for the UK EPR and AP1000 were organised into 18 technical topic areas in each of which the Requesting Parties were required to satisfy Inspectors that their proposed design complied with accepted UK safety, security and environmental regulations and practices. These topic areas are listed in Table 1.

Internal Hazards
Civil Engineering and External Hazards
Probabilistic Safety Analysis
Fault Studies
Containment and Severe Accidents
Control and Instrumentation
Electrical Engineering
Fuel Design
Reactor Chemistry
Radiological Protection
Mechanical Engineering
Structural Integrity
Human Factors
Radioactive Waste and Spent Fuel Management
Management of Safety & QA
Cross cutting Issues
Security
Environmental Impacts

Table 1: The 18 Technical Topic Areas

The objective of the present study is to identify the most important safety and environmental issues that would be likely to arise in a hypothetical GDA of an SMR design, and to propose possible arguments for addressing them.

The following methodology was adopted for the study:-

1) The ONR Safety Assessment Principles (SAPs) [2] and EA RSR Environmental Principles (REPs) [3] were reviewed to identify UK regulatory expectations judged likely to significantly affect acceptance and permitting of the SMR designs.
2) Publicly available ONR/EA assessment reports produced in the GDAs of the UK EPR and AP1000 were reviewed to identify issues raised by the regulators that would be likely to apply to the SMRs. As the EPR and AP1000 are both PWRs, it is expected that the issues identified by investigation of these GDAs will have the greatest relevance for the PWR-type SMRs, but they should provide also guidance for the less familiar molten salt, liquid metal and high temperature gas designs.
3) Workshops/meetings with ONR and EA were organised to obtain the regulators' views on the validity of the issues identified in steps (1) and (2) and identify any missing items. A detailed set of minutes from the workshop with ONR are included in [4].
4) Issues likely to have strong effect on the proposed reference SMR designs and GDA acceptance timescales were identified based on design information submitted to the TEA process by SMR vendors, which was limited in some cases. For each issue, recommendations were made on possible approaches by which it could be addressed to facilitate the GDA acceptance process. It must again be emphasised that as experience from previous GDAs is mainly for PWRs, a much greater degree of judgment is needed when attempting to predict just which regulatory requirements will apply to the non-PWR designs. This is compounded by fact that the depth of information available, and the development of the designs, is much less substantial for the non-PWR designs.

The identification of key issues and proposed arguments for addressing them are presented in Section 3 below.

Although the SMR designs submitted to the TEA have electrical outputs that are far below those of the plants considered in previous GDAs, application of the usual scaling principles indicates the potential radiation doses due to within and beyond design-basis accidents in these plants would still be above the levels at which relaxation of the UK deterministic safety requirements (as presented in ONR SAPs [2]) could be justified. In addition, RSR Regulatory Environmental Principles would apply to an SMR in respect of operational releases of radioactivity and discharges and disposals of radioactive waste. Therefore it was assumed for the purposes of the current assessment that the fundamental design and safety requirements applied by ONR and the Environmental Agency in the GDAs of the large reactors would also apply to an SMR. The validity of this assumption was confirmed in discussions with the regulators themselves[4].

3 REVIEW OF ISSUES AFFECTING SMR LICENSABILITY

3.1 Requirements inferred from the ONR SAPs

The key SAPs considered likely to have the greatest impact on SMR designs and GDA acceptance timescales are summarised in Volume II of this report. The different types of SMR design were reviewed against these SAPs, and against the EA REPs, using design information provided to the TEA by the participating SMR vendors.

3.2 Requirements inferred from previous GDA outcomes for New-Build Reactors

To identify current regulatory expectations and requirements applied to new-build reactors, a review was carried out of ONR and EA assessment reports published on the ONR and EA websites for the EPR and AP1000 designs. The review is described in detail in Volume II of the current report. The regulatory expectations and requirements inferred from previous GDAs are potentially relevant to all SMR designs but especially to the SMRs utilising PWR technology. There also some matters that arise from the review of the SAPs for the non-PWR designs that are not of great significance to the PWRs currently undergoing GDA.

The review of GDA outcomes identified some 28 "high impact" regulatory expectations and requirements that either resulted in modifications to the reference plant designs, or significantly affected GDA completion timescales. The designs of the participating SMR vendors were reviewed against these 28 issues to identify their relevance, using design information provided to the TEA by those vendors.

3.3 Results of pre-GDA Assessment

This section identifies the significant regulatory issues identified from the review described in Sections 3.1 and 3.2, and presented in detail in Volume II.

The structure adopted is:-

- Each issue is discussed in turn.
- The generic reactor type(s) to which the issue is most likely to be applicable is/are identified.
- Where possible recommendations are made of ways in which the issue could be addressed to facilitate the GDA acceptance process.

3.3.1 Classification and diversity requirements placed on protection systems

3.3.1.1 Description of issue

In the GDA of the large reactors, the Requesting Parties were required to perform design basis analysis of faults and hazards to demonstrate that significant core damage would be avoided in all fault/hazard sequences with a frequency of occurrence greater than 10^{-7} per year. Protection systems and measures credited in the design basis analysis were required to be nuclear safety classified (i.e. designed and operated to accepted nuclear design codes and standards). These requirements resulted in the following detailed requirements:

- Requirement to demonstrate at least one nuclear safety classified means is available for achieving the critical safety functions of reactivity control, decay heat removal and containment of radioactivity in all design basis faults and hazards
- Requirement to demonstrate that the design includes two diverse, independent and nuclear safety classified means of achieving the critical safety functions of reactivity control, decay heat removal, and containment of radioactivity, in 'frequently occurring' faults and hazards (defined as initiating events with frequency above one in one thousand years) in all plant states

The above requirements were not met in all cases by the large reactors designs submitted to GDA, resulting in need for design changes. Similar shortfalls may apply to SMRs. Particular issues are as follows:

1) Decay heat removal in frequent faults during power operation

The PWR-type SMRs submitted to the TEA generally use passive decay heat removal concepts and in most cases two alternative passive means of cooling can be identified, partially satisfying the UK diversity requirement. However in many cases both systems appear to use some common means of heat rejection, which is unlikely to satisfy fully the requirement for diversity and independence. (For example in some of the SMRs, both means of cooling appear reliant on achieving leak tightness of the primary containment vessel). Potential shortfalls against UK requirements may be significant.

This requirement for diversity in decay heat removal is also applicable to non-PWR type SMRs. However insufficient information is available from the TEA to establish if adequately diverse systems for decay heat removal are provided for these designs.

2) Decay heat removal during shutdown

The requirement for two independent and diverse and nuclear safety classified means of removing decay also applies in other permissible reactor states including shutdown states. No evidence was found for any of the SMR designs submitted to the TEA that a safety classified means is available for decay heat removal in faults in shutdown states, or that diverse methods are available for cooling a shutdown reactor in frequent faults and hazards. Potential shortfalls against UK requirements may be significant in some cases. For the PWR-type reactor designs, about which the most detail is available, the passive decay heat removal systems do not appear to be effective in all shutdown states.

3) Decay heat removal in fuel handling and storage

Experience from GDAs of larger plants suggests shortfalls against UK requirements for classified protection against all credible faults in fuel handling and storage may lead to the need for significant design changes. For example there was a requirement on designers of the UK EPR to provide an additional barrier for preventing coolant leakage from the fuel transfer tube during fuel handling operations.

For the PWR-type SMRs submitted to the TEA, spent fuel pool cooling appears reliant on a single safety-classified means (removal of thermal energy by passive boil-off of the pool). Lack of diverse cooling may be acceptable due to the long timescales available before fuel dryout, assuming there are no credible faults that could cause pool draining. In contrast, no evidence is provided that nuclear safety classified cooling means are available in credible faults during fuel handling, when fuel is being moved between the reactor and the spent fuel pool. For the non-PWR designs no evidence is provided to determine if safety classified means are provided for cooling of spent fuel during either storage or handling. Potential shortfalls against UK requirements may be significant in some cases.

4) Reactivity control during power operation

UK requirements are for two independent, diverse and nuclear safety classified means of shutting down the reactor to be available in frequently occurring faults and hazards. For most of the PWR-type SMRs submitted to the TEA, independent means of shutdown are provided by control rod insertion and boron injection into the primary system. However some potential shortfalls against UK requirements can be identified:

- The boron injection systems may not be capable of achieving reactor shutdown in all faults that are regarded as frequently occurring in the UK (e.g. secondary system depressurisation faults).
- In cases where boron injection is achieved using pumped systems, these systems do not appear to be nuclear safety classified.
- Some PWR-type SMR designs use control rod drives that are internal to the reactor pressure vessel, and are therefore exposed to high pressure and high temperature conditions and significant temperature transients. There appears limited previous experience with such internal CRDMs to back up reliability claims for such systems.

For the non-PWR type SMRs submitted it is not clear that two independent means are provided for achieving reactor shutdown with adequate reliability.

5) Reactivity control in shutdown states

For PWR reactors, achieving an adequate shutdown margin in cold shutdown states requires boration of the primary coolant. Accidental dilution of the borated coolant could lead to an unacceptable reactivity excursion in such conditions. In the UK, such dilution faults are regarded as potentially frequently occurring events, requiring two diverse means to accommodate them

In the GDA of large PWRs this requirement led to requirements for the modification of protection systems resulting in increased design cost and complexity.

For the PWR-type SMRs no evidence is provided that appropriate safety-classified means are provided to prevent reactivity excursions in potential boron dilution events in cold shutdown.

More detailed safety cases would be needed to identify the applicability of the requirements for reactivity control in shutdown states to non-PWR SMRs. (The boron dilution issue will not apply.)

6) Containment cooling following a small break loss of coolant accident

The diversity principle requires two independent and diverse means of containment cooling to be available to prevent radioactivity releases in frequently occurring faults and hazards (such as frequent small-break loss of coolant accidents). This principle appears not to be generally met by the PWR-type SMRs as they rely on a single passive containment cooling system to prevent overpressurisation of the primary containment vessel in frequent loss of coolant accidents. The result of the shortfall may be a requirement for an additional nuclear safety classified containment cooling system.

7) Diversity/Classification of reactor overpressure protection systems

In the GDA of the AP1000 design, ONR noted that faults involving loss of steam generator feed water (considered to be a frequent) resulted in opening of the primary pressure relief valves, and that no diverse, independent means of primary system overpressure protection was available. This conflicted with the requirement for diverse protection against frequent faults and hazards.

A similar issue may apply to PWR-type SMRs, which may experience even greater over-pressures loss of secondary side cooling faults, due to the smaller relative volumetric capacity of the once-through steam generators used in these designs.

To meet the diversity principle, a possible modification would be to implement a second independent means of primary pressure relief in addition to the primary pressure relief valves. Alternatively a nuclear safety classified backup feed system could be provided which would prevent relief valves from opening in frequently occurring faults that cause a loss of secondary side cooling. Both of these alternatives would represent potentially significant design modifications.

8) Diversity/classification of electrical support systems

In GDAs of large reactors ONR have requested that the design basis analysis demonstrated that UK requirements for diversity and safety classification of the electrical support systems were met in all fault conditions, including shutdown faults and faults in the Spent Fuel Pool. As the large reactor designs did not generally include two diverse and safety classified, electrical support systems, the UK requirements have resulted in the need for significant modifications. Similar design impacts might arise for an SMR design.

3.3.1.2 Generic reactor type to which the issue applies

The issue to applies to all SMRs.

3.3.1.3 Recommended response to diversity/classification issue

Should a requirement for equipment upgrades or new diverse backup systems be indicated to meet the classification and diversity principles applied in design basis analysis in GDA, it is recommended that SMR vendor performs a holistic risk-informed cost-benefit ALARP analysis to justify that the cost and difficulty of the plant modification was justified against the reduction in risk that can be achieved. Such an assessment should ideally use a full-scope probabilistic safety analysis (PSA) to assess realistically the impact on core melt frequency and the large radiological release frequency of the proposed modification.

A PSA analysis of the risk benefits of implementing diverse and safety classified backup to a front-line safety system would depend on the assumed reliability of the front-line system due to common cause failure (CCF). CCF analysis techniques have undergone significant developments in recent years. Notably, the USNRC has developed a methodology [5] for predicting CCF in multiply-redundant systems and has published [6] tables of recommended CCF parameters The USNRC CCF methodology includes a method for predicting CCF rates for the important case where no prior failure data is available, which is often the case with new reactor designs. It is recommended that the USNRC method, or an equivalent state-of-the-art method, is used for determining CCF rates in a PSA cost-benefit analysis.

If the SMR vendor concludes that that a particular design enhancement is not reasonably practical for his particular plant, the onus is on him to make the safety case to the regulator. Our interactions with the regulator lead us to the view that the regulator is very open to such discussions.

3.3.2 Avoidance of criticality in the Spent Fuel Pool

3.3.2.1 The issue

There is a UK requirement (Ref [2] Principle ECR.1) that only passive means should be used to control criticality in storage of fissile materials. This results in a need to demonstrate avoidance of criticality in a spent fuel pool relying only on geometry and fixed absorbers, with no reliance on dissolved absorber in the coolant. This issue has affected the design of a large PWR submitted for GDA, and may require modifications to the fuel storage pond design for some of the SMR-type PWRs.

3.3.2.2 Generic reactor type to which it applies

The concern regarding avoidance of criticality in the fuel storage pool without reliance on dissolved absorbers in principle will apply to any water-filled storage pool. It is highly likely to apply to PWR-type SMRs.

3.3.2.3 Recommended response

Avoidance of any dependency on a dissolved absorber to prevent criticality in fuel storage is a well-established UK principle, which can only be addressed by appropriate design measures. It is therefore recommended that early attention is given to this issue in a GDA assessment of any SMR design so that any design changes, if necessary, can be identified and implemented.

3.3.3 Radioactivity releases in steam generator tube rupture events

3.3.3.1 The issue

In the GDA of one of the large PWR design, concerns were raised by ONR that radioactivity releases in some frequently occurring steam generator tube rupture (SGTR) events were close to allowable limits defined in numerical targets in the SAPs (Ref [2] Target 4). This issue, which applies to a limited range of events close to the frequent/infrequent boundary (10^{-3} per year), may be more severe in the small PWRs as these plants have integral steam generators whose small internal volume may lead to increased discharge of radioactive liquid coolant to the environment in SGTR events.

3.3.3.2 Generic reactor type to which it applies

The concern is only applicable to PWR-type SMRs due to their use of pressurised liquid coolant with a significant radioactivity content.

3.3.3.3 Recommended response

If the UK target for the maximum permissible radioactivity releases is found to be exceeded in frequently occurring SGTR events, a possible response would be to modify the plant design to use smaller diameter steam generator tubes to reduce leak flow rates, or to relocate the steam relief valves, or to provide greater void capacity to reduce liquid discharge.

Considering that physical modifications to plant could have undesirable consequences on heat transfer performance and space and layout requirements, it is recommended that before implementing such plant modification an SMR vendor should first perform a holistic risk-informed cost-benefit ALARP analysis to justify that the cost and difficulty of the modification was justified against the reduction in risk that could be achieved, using the approach discussed above in Section 3.3.1.3.

3.3.4 Requirement for filtered discharge from the fuel building in the event of loss of cooling of spent fuel pond

3.3.4.1 The issue

In the GDA of the AP1000 design, in which the safety classified means of cooling the spent fuel pool relies on removal of thermal energy by passive boil-off of the pool, ONR requested that blowout panels and a filtered discharge route for steam relief were installed in the fuel building. As most PWR-type SMRs use a passive heat removal concept similar to the AP1000 used for spent fuel cooling, similar modifications may be requested.

No information is available on proposed arrangements for spent fuel cooling for the non-PWR SMRs, so it is not known if a similar issue would apply.

3.3.4.2 Generic reactor type to which it applies

The issue is potentially applicable to all SMR designs in which spent fuel is stored in a water pool.

3.3.4.3 Recommended response

If this issue arises for an SMR, it is recommended that SMR vendor should first perform a holistic risk-informed cost-benefit ALARP analysis to justify that the cost and difficulty of the modification was justified against the reduction in risk that could be achieved, using the approach discussed in Section 3.3.1.3.

3.3.5 Requirement to provide a containment filtered vent for severe accident conditions

3.3.5.1 The issue

Following the Fukushima accident, ONR requested that, for the large PWRs undergoing GDA, consideration was given to installing a filtered containment vent to reduce the potential radiological consequences of core melt events involving complete loss of containment cooling. A similar request may be made for the PWR-type SMRs.

3.3.5.2 Generic reactor type to which it applies

The issue is applicable to some PWR-type SMRs: its applicability to non-PWR designs is unknown.

3.3.5.3 Recommended response

The recommended response is similar to that proposed in Section 3.3.4.3 in relation to the installation of additional filtration for the fuel building.

3.3.6 Requirement for heavy load drops from nuclear lifting devices to be considered in the design basis

3.3.6.1 The issue

In the GDA of the UK EPR, ONR noted that accidental drop of heavy loads from critical lifting devices such as the polar crane and the fuel cask-handling crane had been excluded from the design basis due to their high standards of design and operation, and the need for multiple failures to occur to cause a load drop. ONR considered that the exclusion of such events was inconsistent with UK design basis principles, requesting that worst-case load drops from all lifting devices were included in the design basis analysis. In the case of the UK EPR design, this resulted in significant design changes to increase structural reinforcement of the reactor building and to improve protection against consequential loss of coolant accidents during refuelling.

If heavy load drops have been excluded from the design basis of the SMRs designs, similar issues may arise in a GDA. It is noted that specific design features of some SMRs, such as the use of integral RPVs whose upper sections contain internal steam generators and CRDMs, could potentially result in significant dropped load consequences.

3.3.6.2 Generic reactor type to which it applies

The issue would potentially apply to all SMRs in which heavy lifting operations are performed using a polar crane or similar device.

3.3.6.3 Recommended response

It is recommended that the requirement to address the consequences of load drops from all lifting equipment in the design basis analysis is identified to SMR vendors at an early stage of GDA, to minimise delays in in GDA acceptance of an SMR design.

3.3.7 Missile impacts from gross failure of pressure parts

3.3.7.1 The issue

In the GDA of the large PWRs, ONR noted that the risk from missiles due to failure of pressure parts designed to nuclear codes such as ASME III or RCC-M had been discounted on the basis of their high standard of design and construction. ONR considered that catastrophic failure could only be excluded for High Integrity Components (HIC; see below) and therefore requested that an assessment of the consequences of missiles from catastrophic failures of non-HIC pressure vessels, tanks, pumps and valves was included in the design basis analysis. It is likely that a similar requirement will arise for SMRs.

Some SMRs have pressurized tanks, valves and pipework located close to the containment wall. Potential damage to the containment vessel due to missiles produced by failure of these may be of concern.

3.3.7.2 Generic reactor type to which it applies

This issue appears to apply to all SMRs.

3.3.7.3 Recommended response

It is recommended that the requirement to address the consequences of missile impacts due to failure of all pressure parts (except HIC) in the design basis analysis, is identified to SMR vendors at an early stage of GDA, to minimise delays in in GDA acceptance of an SMR design.

3.3.8 Flooding due to gross failure of pressurised systems

3.3.8.1 The issue

In the GDA of the large PWRs, ONR noted that the risk from internal flooding due to guillotine failure of nuclear safety classified low-pressure pipework above 50mm in diameter had been discounted due to their assumed high standards of design and construction. ONR considered that guillotine failures could only be excluded for components classified as HIC (see below). They therefore requested that the consequences of flooding from guillotine failures of pipes above 50mm diameter were addressed in the design basis analysis. ONR further requested that the consequences of internal flooding were shown to be acceptable without claims on operator intervention, unless it was not reasonably practicable to do so, and that protective measures against flooding consequences were designed to nuclear codes and standards.

The above requirements resulted in significant design changes for one of the large PWR designs. They are expected to apply equally to SMR designs but their impact will depend on the extent to which pumped cooling systems are used in these designs.

3.3.8.2 Generic reactor type to which it applies

This issue appears to apply to all SMRs using pumped cooling systems.

3.3.8.3 Recommended response

It is recommended that the requirement to address the consequences of internal flooding due to guillotine failure of nuclear safety classified low-pressure pipework above 50mm) in the design basis analysis, and the need to use automatic rather than manual means for flood protection (subject to ALARP), are identified to SMR vendors at an early stage of GDA, to minimise delays in in GDA acceptance of an SMR design.

3.3.9 Failure of 'passive' valves

3.3.9.1 The issue

In the GDA of the large PWRs, ONR considered that failures of check-valves (non-return valves) to close or open, and the failing shut of normally open valves, should be postulated as additional 'single failure' events in design basis analysis. Such failures had been excluded in the design basis analysis presented by the Requesting Parties, as it is conventional practice outside the UK to treat them as 'passive' failures, which do not need to be considered in applying the single failure principle.

The above requirements have had a significant impact on the design of the large PWRs. Similar requirements are expected to apply to the PWR-type SMRs and may lead to the need for additional valves or other plant modifications.

3.3.9.2 Generic reactor type to which it applies

This issue appears to apply in principle to all SMRs but is particularly significant for the PWR-type SMRs that use multiple check-valves and manually operated valves in their emergency cooling systems.

3.3.9.3 Recommended response

If this issue results in the potential need for design changes in an SMR, it is recommended that, before a plant modification is implemented, the SMR vendor should first perform a holistic risk-informed cost-benefit ALARP analysis to justify that the cost and difficulty of the modification was justified against the reduction in risk that could be achieved, using the approach discussed in Section 3.3.1.3.

3.3.10 Requirement for testing/qualification of pyrotechnic valves

3.3.10.1 The issue

Some of the PWR-type SMRs use pyrotechnic-operated (SQUIB) valves for depressurising the reactor to initiate passive emergency cooling systems. The use of SQUIB valves was questioned by ONR in the GDA of the AP1000 PWR, due to concerns about maintainability, design development status, qualification for use in high radiation environments, risk of spurious actuation due to fires etc. Similar concerns would likely be raised for SQUIB valves used in SMRs.

3.3.10.2 Generic reactor type to which it applies

This issue applies to any SMRs that employ them; the PWR-type seems the most likely to be affected. We are not aware that they are proposed on others.

3.3.10.3 Recommended response

For SMRs that use pyrotechnic valves in safety systems it is recommended that R&D evidence be identified by the vendor at an early stage of GDA to establish that sufficient testing and environmental qualification evidence is available to support the reliability claims in the safety case. If the claimed reliability cannot be supported by existing evidence, further testing and/or environmental qualification should be performed as early as possible to address the issue.

3.3.11 Inspection of High Integrity Components

3.3.11.1 The issue

High Integrity Components (HICs) are defined as components (such as the reactor pressure vessel) whose gross failure could lead to unacceptable radiological consequences. In the UK, HICs are subject to unique requirements, including fracture mechanics analysis using approved methods, and qualified inspections by non-destructive examination (NDE) techniques, during manufacture and in service, to show that defects present in welds or forgings will not approach critical dimensions. Both radiographic and ultrasonic NDE methods must be applied using prescriptive methods and independently accredited operators.

The UK requirements for fracture mechanics analysis and inspection of components classified as HIC go beyond those of other jurisdictions, and have significantly affected the design and layout of new-build reactors in previous GDAs. Application of UK HIC requirements to SMR designs is of particular concern, as the compact design of the containment vessel in some SMRs may make access for inspection of HICs difficult. Additionally, an SMR installation containing multiple small reactors could face excessive operating costs and an excessive operator dose burden due to the overall number of HIC welds that might need to be inspected during outages.

3.3.11.2 Generic reactor type to which it applies

This issue potentially applies to all SMRs.

3.3.11.3 Recommended response

It is recommended that an SMR vendor be requested to take into account of the UK inspection requirements an early stage of the GDA process by identifying the components and welds that are to be classified as high integrity components, and by identifying the inspection method that will be applied in each case, taking account of access constraints.

It is noted that the UK has been a leader in the development of NDE techniques for detecting defects in pressure boundary components. Research has both improved the ability to detect defects in complex geometries, and has also focused on "condition monitoring" techniques that allow semi-continuous and remote assessment of components. This research has been resulted in effective commercialization of advanced techniques, and widespread use, for example in LNG applications.

In view of the potential opportunity for utilising UK expertise in NDE required by SMRs it is recommended that as part of an SMR program, consideration be given to initiating a significant research programme in the NDE area, capitalizing on the existing UK expertise. The methods development, and indeed the performing of the inspections, is a high value-added activity, where the United Kingdom could both contribute and benefit significantly

3.3.12 Design of Class 2 pressure equipment

3.3.12.1 The issue

In the GDA of the large PWRs, ONR requested that pressurised systems providing both the main and backup safety functions in the design basis analysis should be designed to nuclear design codes such as ASME III. In the reference designs of the large PWRs, backup systems and some front line systems had been designed to non-nuclear codes and standards for economic and procurement reasons. The requested design upgrade particularly affected the design of pumped cooling systems such as the residual heat removal system and its cooling chain. It is probable that the pumped cooling systems of the SMRs will similarly be designed to non-nuclear mechanical codes, and the requirement may therefore have a significant design and economic impact.

3.3.12.2 Generic reactor type to which it applies

This issue potentially applies to all SMRs.

3.3.12.3 Recommended response

If this issue results in the potential need for design changes in an SMR, it is recommended that, before a plant modification is implemented, the SMR vendor should first perform a holistic risk-informed cost-benefit ALARP analysis to justify that the cost and difficulty of designing pressure parts to nuclear rather than industrial codes would be justified against the reduction in risk that could be achieved, using the approach discussed in Section 3.3.1.3.

3.3.13 Requirement for demonstration that operator doses are ALARP

3.3.13.1 The issue

In the GDAs of large reactors, Requesting Parties were required to provide evidence that radiation doses to workers in normal plant operation and accident conditions were as low as reasonably practicable (ALARP) and to provide detailed justification of the radiological zoning scheme and the dose rate predictions for occupied areas.

Similar detailed evidence showing that operator doses have been reduced to ALARP and that appropriate shielding analysis has been performed to support radiological zoning for occupied areas is also likely to be required for a GDA of a UK SMR. This may require significant development of the detailed plant design, which could increase the time for GDA acceptance.

3.3.13.2 Generic reactor type to which it applies

This issue applies to all SMRs.

3.3.13.3 Recommended response

The current requirement on vendors to provide a justification of why assessed operator dose levels could not be practicably reduced, even when the assessed doses are below legally acceptable limits, may not be known to SMR vendors. It is recommended that the need to provide detailed information on operator radiation exposure in operating the plant, and the measures taken to minimise exposure, should be identified to vendors at an early stage of GDA, to allow maximum time for the development of the detailed design and so minimise delays in in GDA acceptance.

3.3.14 Software-based control and instrumentation (C&I) systems

3.3.14.1 The issue

To meet the UK requirements for diversity and classification, two nuclear safety classified C&I systems of diverse design must be provided to perform the main and backup safety functions in a nuclear plant. For large reactors submitted to GDA it was also requested that C&I system delivering the back-up safety functions should use non-programmable technology so as to be fully diverse form the main C&I protection system that used programmable digital technology. These requirements have led to extensive design modifications for large reactors previously submitted for GDA. Similar requirements to provide a safety-classified non-computerised C&I system as back up to the main computerised protection system, would also be expected to apply to a UK SMR. Such requirements may also have a significant impact on the SMRs designs.

3.3.14.2 Generic reactor type to which it applies

This issue applies to all SMRs.

3.3.14.3 Recommended response

The UK requirement to provide a non-computerised C&I system as a backup to the digital primary protection system arises from fundamental and deeply established concerns about the complexity of programmable systems, and the potential for common cause failures due to undetected software errors. It is recommended that the requirements be identified as early as possible in the GDA of an SMR so that necessary design changes can be implemented early in a GDA process.

It is further recommended that research into software reliability should be performed to help achieve UK regulatory acceptance of software-based safety systems in SMRs and other nuclear plants. In particular it is recommended that a research programme should be established in software specification, design and testing with the aim of raising the general level of confidence in the use of software in safety critical nuclear applications. This would indeed have benefits that go well beyond just the nuclear sphere and would also build on, and foster, a good base of expertise in the UK. In the shorter term, it is also recommended that a complementary research program be initiated to identify and understand the way in which software is used in safety critical applications outside the nuclear sector, along with an assessment of how such usage could be mapped across into the nuclear sphere.

3.3.15 Design of human machine interface in control rooms

3.3.15.1 The issue

For the large PWRs submitted to the GDA the Human Machine Interface in the Main Control Room and Remote Shutdown Station, communicating with Class 1 systems, was required to be designed to Class 1 standards. This had a significant effect (both cost and time) on the design acceptance process. It is likely that similar requirements would be placed upon SMRs to be licensed in the United Kingdom.

3.3.15.2 Applicable to:

This issue applies to all SMR types and designs.

3.3.15.3 Recommended responses

It is recommended that the requirement to design the Human Machine Interface communicating with Class 1 systems to Class 1 standards, is identified to SMR vendors at an early stage of GDA, to minimise delays in in GDA acceptance.

3.3.16 Qualification requirements for software used in nuclear safety classified equipment.

3.3.16.1 The issue

In GDA of the large reactors, Requesting Parties were required to implement 'independent confidence building measures' and 'production excellence measures' to qualify the design of software used in nuclear safety classified C&I systems. The software qualification and testing requirements were graded depending on the safety importance of the system. For the main digital protection systems the requirements included statistical testing, static and dynamic analysis and compiler validation. The qualification requirements also apply to software embedded in instruments and actuators provided by equipment manufacturers.

Similar requirements are likely for safety classified software based systems used in SMRs, potentially requiring significant further design development and testing which could increase the duration of GDA.

3.3.16.2 Applicable to:

This issue applies to all SMR types and designs.

3.3.16.3 Recommended responses

The above software qualification and testing measures are not applied outside the UK and are unlikely to be known to an SMR vendor. It is therefore recommended that the UK requirements for software qualification and testing are identified to SMR vendors at an early stage of GDA, to minimise delays in in GDA acceptance of an SMR design.

The proposed research programme in software specification, design and testing, recommended in Section 3.3.14.3 would be also potentially useful in assisting the licensing acceptance of the software qualification measures proposed by an SMR vendor.

3.3.17 Design of standby diesel generators

3.3.17.1 The issue

In the AP1000 design submitted to GDA, the standby diesel generators were not nuclear safety classified, as it was argued that the main protection functions were provided by passive means that did not require AC power. ONR questioned whether the diesels should be designed to nuclear codes and standards and requested that a safety case be produced justifying the lower classification. It is not clear whether a reclassification of the standby diesel generators will eventually be required, but such a change could significantly affect the design of the diesels and buildings that house them.

Similar issues would likely arise in a GDA on an SMR, if nuclear safety classified standby diesels are required.

3.3.17.2 Applicable to:

All SMR designs that use standby diesel generators that are not designed to nuclear codes and standards.

3.3.17.3 Recommended responses

If this issue arises for an SMR, it is recommended that, before a plant modification is implemented, the SMR vendor should first perform a holistic risk-informed cost-benefit ALARP analysis to justify that the cost and difficulty of designing the standby diesel generators to nuclear rather than industrial codes would be justified against the reduction in risk that could be achieved, using the approach discussed in Section 3.3.1.3.

3.3.18 Justification of human reliability claims

3.3.18.1 The issue

In GDA of the large PWRs, ONR expected the safety submissions of the Requesting Parties to identify all human actions credited in the design basis analysis and probabilistic safety analysis, provide justification of the human error probabilities claimed, and demonstrate that the risk from these actions was ALARP.

ONR noted that some significant potential human errors had been omitted from the initial safety analyses provided by the Requesting Parties, particularly errors in maintenance, errors resulting in the initiation of faults and hazards, and errors in performing post-fault mitigation and recovery actions.

To meet ONR expectations, the Requesting Parties in previous GDAs have performed extensive additional analyses to identify safety-important human error conditions, to justify claimed human error probabilities and to demonstrate that the risk from the human actions was ALARP. The new analyses were validated using trials on plant simulators.

It is assumed that a similar level of human error analysis and justification would be required in the GDA of an SMR. As the design development status and safety documentation available for the SMRs is more limited than for the larger plants, new analysis may be required which could extend the timescales for GDA acceptance.

3.3.18.2 Generic reactor type to which it applies

This issue applies to all SMR types and designs.

3.3.18.3 Recommended response

The requirement for a reactor safety report to provide an in-depth analysis of potential human error consequences, before plant construction, is well established in the UK. Therefore it is recommended that the requirement should be identified to an SMR vendor as early as possible during GDA so that the human error justification can be provided with minimal delays in GDA acceptance.

3.3.19 Human factors analysis to justify plant staffing

3.3.19.1 The issue

Plant staffing requirements may be a key Human Factors issue for smaller SMRs, particularly in cases where a single control room serves multiple reactor units. Although there is some UK experience of twin reactors sharing a common control room, previous practice has been to have one desk operator per unit in a control room at all times, backed by a supervisor to provide desk cover during short absences. In some SMR concepts, 8 or 12 reactors are proposed in a single installation and allocation of one desk operator per unit may not be feasible.

To justify plant staffing proposed for SMR operation a comprehensive human factors analysis of critical safety actions, including control room actions and maintenance and post-fault recovery operations would be required. Achieving regulatory acceptance of this analysis could be a key licensing issue for the SMRs, particularly for those designs with more than two reactors in a single installation.

3.3.19.2 Generic reactor type to which it applies

The issue applies to all SMRs, but will have an impact particularly for those with more than two reactor units within a single installation.

3.3.19.3 Recommended response

The requirement for an in-depth human factors analysis of plant operation to justify manning arrangements is well established in the UK but may not be known to a SMR designer. Therefore it is recommended that the requirement should be identified to an SMR vendor as early as possible during GDA so that the human error justification can be provided with minimal delays in GDA acceptance.

3.3.20 Demonstration that plant chemistry control achieves ALARP

3.3.20.1 The issue

SAPs Principle ECH.1 requires that the reactor safety case should demonstrate how plant chemistry controls affect safety in normal operation and fault conditions, to show that proposed controls reduce risk to ALARP. In the GDA, this requirement resulted in Requesting Parties being required to provide additional justification of many chemistry aspects including optimisation of chemistry to: protect fuel and structural materials; to minimise radiation doses in normal operation and accidents; and to minimise arisings and discharges of radioactive waste.

In the case a large PWR submitted to GDA, ONR raised significant concerns regarding the chemistry safety case in respect of the source term in severe accidents, the arrangements for sampling of primary coolant, and arrangements for control of coolant hydrogen dosing. IN GDA of the ABWR design a Regulatory Issue was raised requiring the Requesting Party to provide a demonstration that coolant chemistry controls satisfy ALARP.

As the design development status of the SMRs is less advanced than that of the larger plants it is expected that a proposed SMR reactor chemistry regime would also need further development to demonstrate that the coolant chemistry has been optimised to achieve ALARP. This design development activity could significantly extend GDA timescales.

3.3.20.2 Generic reactor type to which it applies

This issue applies to all SMR types and designs.

3.3.20.3 Recommended response

The requirements for a chemistry safety case is well established in the UK but are unlikely to be known to an SMR vendor. Therefore it is recommended that the requirement should be identified to an SMR vendor as early as possible during GDA so that the chemistry safety case can be provided with minimum delays in GDA acceptance.

3.3.21 Requirement for safety and environmental report and frozen reference design

3.3.21.1 The issue

For the GDA of the large reactors, a detailed design description and the safety and environmental case were required to support the proposed reactor design. In particular, Requesting Parties were required to define a 'frozen' reference design for the systems, structures and components important to nuclear safety, at a level of detail corresponding broadly to that in an equipment procurement specification. The safety and environmental case was required to be clearly linked to the reference design, and changes to the reference design made during GDA to be controlled by an approved change management procedure.

The designs and safety cases of the SMRs are less advanced than those of the plants submitted to previous GDAs so it is expected that their design and safety and environmental documentation would need significant further development to reach the level of detail expected. The requirements for detailed documentation are expected to have a significant effect on timescales for completing the GDA of an SMR.

3.3.21.2 Generic reactor type to which it applies

This issue applies to all SMRs.

3.3.21.3 Recommended response

The requirement for a frozen and fully documented reference design linked to a safety and environment report is fundamental to the GDA process but is unlikely to be known to an SMR vendor. Therefore it is recommended that the requirement to define a frozen reference backed by a detailed design description, together with a consistent safety and environment report, should be identified to an SMR vendor as early as possible in the GDA process to minimise delays in GDA acceptance.

3.3.22 Safety requirements for a nuclear facility containing multiple reactors

3.3.22.1 The issue

As discussed in Section 3.3.19 above several of the SMR concepts envisage a single installation containing multiple small reactors with sharing of services such as use of single control room. There is some UK experience of twin reactors sharing services (for example at Oldbury Power Station a single fuelling machine served two Magnox reactors, and both reactors shared a common control room). However for some of the proposed SMRs this practice is taken much further with 8 or 12 reactors being proposed in a single installation. Such multiple unit plants would create various challenges as follows:

Interactions between units

Discussions held with ONR[4] confirmed that for installations containing multiple reactors the safety case for the installation would have to address common cause failures that could affect several units (such as loss of common electrical services), and possible propagation of faults from unit to unit. In general ONR considered that sharing of safety-significant equipment between reactors was undesirable and in conflict with IAEA principles.

Staffing

Discussions held with ONR[4] confirmed that it would be acceptable in principle for a single desk engineer to operate more than one reactor unit at one time, provided an acceptable human factors safety case could be made. ONR noted that overall manning numbers on-site must be sufficient to enable recovery from faults and hazards affecting multiple units. The environmental regulators would also need to consider potential impact of shared resources on environmental impacts.

Outage scheduling

ONR also pointed out that manpower requirements for simultaneous maintenance and refuelling activities on multiple units in a single installation could be prohibitive. If it was proposed to shut down the units for refuelling one unit at a time (to reduce the number of refueling crews required), ONR considered that a very robust safety case would be needed to allow units to operate in the vicinity of units that were shut down.

3.3.22.2 Generic reactor type to which applicable

The above issue applies to all SMRs in which an installation includes more than two reactors.

3.3.22.3 Recommended response

The above issues associated with SMRs in which there are more than two reactors in a single installation appear fundamental. If an SMR design of this type was to enter GDA it is recommended that the safety, security and environment report should address the entire installation rather than just a single unit, to take into account interactions between units. This recommendation was confirmed in discussions with ONR[4].

3.3.23 Use of liquid sodium as a coolant

3.3.23.1 The issue

There are several generic issues associated with the use of sodium coolant, which include:

- As with other liquid metals, sodium is opaque. 'Visual' inspection of vessel internals is complex (e.g. ultrasonic imaging is needed) and not as effective as through water or gas.
- Sodium requires careful selection of materials that come in contact with it, but these issues have largely been solved.
- It undergoes activation as a result of neutron irradiation.
- It reacts violently with water
- It can cause reactivity addition if it is abruptly expelled from the core. (This topic is discussed at more length in Volume II).
- The ability to predict natural circulation and boiling heat transfer reliably is probably less secure than for water (if only because of relative familiarity and experience), but arguably sodium (and liquid metals generally) is such a good coolant that the predictive ability required is perhaps less.
- A sodium-cooled reactor if left to cool will eventually turn into a block of solid sodium metal. This should be relatively easy to avoid, and it has not been a problem in practice, but it is a major issue that needs to be taken into account in a safety and environmental case.
- Management and disposal of contaminated sodium would present significant environmental challenges

3.3.23.2 Applicable to:

This applies to sodium-cooled SMRs.

3.3.23.3 Recommended response

The issues listed are fundamental and would have to be addressed in the design, and the safety and environmental submission, for a sodium-cooled SMR.

3.3.24 Use of lead as a coolant

3.3.24.1 The issue

Issues associated with using lead as a coolant are outlined below. They are basically similar to those arising for sodium but there are some differences.

- As with other liquid metals, lead is opaque. 'Visual' inspection of vessel internals is complex (e.g. ultrasonic imaging is needed) and not as effective as through water of gas.
- The ability to predict natural circulation and boiling heat transfer reliably is probably less secure than for water (if only because of relative familiarity and experience), but arguably lead (and liquid metals generally) is such a good coolant that the predictive ability required is perhaps less.
- Lead is chemically aggressive, and in particular tends to be aggressive at flow speeds normally encountered in nuclear reactors, and in particular in pumps.
- Reactivity addition on voiding is less of a problem than for sodium, in particular because the high boiling point of lead makes voiding unlikely.
- The high density of lead means fuel assemblies can float, and rise to the surface if they inadvertently become free. Similarly, control rods require to be pushed down and held down, if inserted from above into the liquid coolant.
- A lead-cooled reactor if left to cool would turn into a block of solid lead metal. This should be relatively easy to avoid, and it has not been a problem in practice for other liquid metal reactors, but it is one of the major practical issues that needs to be taken into account
- Management and disposal of contaminated lead may present greater difficulties due to the toxicity of lead and its greater potential for groundwater contamination.

3.3.24.2 Applicable to:

This issue applies to lead-cooled SMRs.

3.3.24.3 Recommended response

The issues listed are fundamental and would have to be addressed in the safety and environmental submission for a lead-cooled SMR.

3.3.25 Requirement to demonstrate stability of core reactivity

3.3.25.1 The issue

ONR SAP ERC.3 states that reactivity increases due to unplanned movements within the core, or losses or additions of substances from or to the core, should be prevented in a reactor design.

This SAP principle may be difficult to meet for fast neutron type SMRs for the following reasons:

- Depending on the details of the fuel composition, the amount of reactivity above normal criticality required to enter a prompt-critical condition (in which a rapid excursion in power would occur) may be about only half as much as for a thermal reactor.
- If a prompt-critical state is achieved, the rate of power increase depends largely upon the "neutron generation time". For fast reactors, where there is no waiting time whilst neutrons are moderated, this can be two orders-of-magnitude lower than for thermal reactors, resulting in correspondingly shorter timescales for a power excursion.
- Fast reactors provide more opportunities for inadvertent reactivity additions. In particular with sodium coolant, there is the possibility of a significant reactivity addition being caused by the expulsion of liquid sodium from the core. Such expulsion could occur following coolant flow rate and power mismatches, via the generation of large volumes of sodium vapour, or from violent reactions of liquid sodium with hot fuel under some fault conditions. More generally, the configuration of a fast reactor core is necessarily not the most reactive configuration for that amount of fissile material present (in contrast to a thermal reactor), which inevitably leaves a variety of possibilities for such reactivity additions.

3.3.25.2 Applicable to:

This issue applies mainly to SMRs that are fast reactors.

3.3.25.3 Recommended responses

Technical:

In the past when the UK was actively developing fast reactors, it supported a research programme to develop methods to predict how severe such events would be, and thereby to help understand how robust a containment would need to be to withstand the large energy releases associated with these events. Similar programmes were underway in those other countries developing fast reactors at that time. However the ‘excursion’ problem has not been solved, and indeed it is probably fundamentally not amenable to ‘solution’. In principle one might envisage that designs reliably able to keep the potential explosion contained might be developed.

Regulatory:

There is a possibility that a regulator might judge that use of fast neutron nuclear reactors would not comply with the "ALARP" principle when an alternative option was to use thermal neutron reactors that were very much less prone to the possibility of reactivity excursions.

The issue of demonstrating reactivity stability appears fundamental to fast reactor designs and would likely result in the need for further research and development to underwrite the introduction a fast-neutron SMR into the UK.

3.3.26 Validation of analysis methods for natural circulation cooling

3.3.26.1 The issue

A number of the SMR designs rely on "passive" natural circulation cooling in normal operation or fault conditions or both. Demonstrating the effectiveness of natural circulation cooling has proved a complex and troublesome area in the past (see for example Ref [7]).

An obvious attraction of using natural circulation cooling is the absence of reliance on "mechanical" means for coolant circulation using pumps, which eliminates the possibility of faults due to loss of power to the pumps, or mechanical failure. However developing convincing arguments that natural circulation cooling will be effective under the (typically wide) range of circumstances over which it is likely to be relied upon, is not straightforward.

Broadly speaking, in one-dimensional "pipe-like" geometries and in steady single-phase conditions there is a reasonable predictive capability for natural circulation flows, although conservatisms may be needed to reflect the approximate basis of the treatment. Unsteady flows and two-phase flows are however much more difficult to predict reliably.

Matters are more difficult still in three-dimensional geometries. In this case prediction of the occurrence of thermal 'stratification' is needed, but this is hard to model properly. Modern computational fluid dynamics codes are able to provide predictions of the flow, but these generally prove inaccurate.

In view of these difficulties, predictive methods for natural circulation in SMRs are likely to require extensive experimental validation to achieve regulatory acceptance. Due to the dependence of natural circulation phenomena on fluid properties and geometrical length scales, convincing validation is likely to require testing on equipment of heights close to full reactor scale.

3.3.26.2 Applicable to:

This issue applies to all SMR types relying on natural circulation and buoyancy-driven flows, in normal operation or fault conditions or both.

3.3.26.3 Recommended response

Providing an adequate demonstration of the effectiveness of natural circulation cooling would be fundamental to the GDA acceptance of SMR designs using passive cooling.

It is considered that further research in this area could have significant benefits for supporting an SMR programme. In the United Kingdom, there is a very strong background in developing predictive methods for complex flows of this kind; indeed the field of computational fluid dynamics originated in the UK, and the UK remains a leader in this field. We therefore recommend that consideration be given to initiating a significant focused research program in this area. Such a programme, would provide data potentially useful for more than one SMR type, including non-PWR designs: it would need to combine an appropriate mix of suitable scale measurement facilities, in which relevant phenomena are studied on an economically achievable scale, with a parallel program of the development and validation of computational predictive methods for these flows.

3.3.27 Quantification of discharges during normal operation and demonstration of BAT

3.3.27.1 The issue

A GDA Requesting Party is required to submit a detailed environmental report to the environmental authorities describing the measures deployed to minimise the environmental discharges and the generation of radioactive wastes, to confirm that these satisfy the UK requirement that Best Available Techniques (BAT) are employed. The report must identify trends and fluctuations expected over the lifetime of the facility. It must also provide generic estimates of the annual discharges of radioactive isotopes from a site, and the radiation dose to humans and non-human species close to the site, during both normal operation and in reasonably foreseeable faults over the reactor operating lifetime.

As the designs of the SMRs are less advanced than those of the larger reactors previously submitted to GDA, significant further design development may be needed to create an environmental report at the level of detail required for GDA. This could have a significant effect on GDA timescales. For the PWR-type SMRs no environmental issues have been identified that are more challenging than those faced by larger PWRs that have been submitted for GDA, none of which has so far presented significant difficulties. However SMR designs using liquid metal, molten salt and gas cooling the waste streams would be unfamiliar to the UK regulator, and a significant increase the length and difficulty of the environmental assessment would be expected.

3.3.27.2 Applicable to:

This issue would be expected to apply to all SMR types.

3.3.27.3 Recommended response

The requirement for a detailed environmental report with the scope described in Section 3.3.27.1 is fundamental to the GDA process, but is unlikely to be known by an SMR vendor. It is recommended that a Requesting Party for an SMR GDA should take account of the documentation requirements at the start of the GDA process to minimise delays in achieving GDA acceptance.

4 DISCUSSION AND SUMMARY OF MAIN RECOMMENDATIONS

The pre-GDA review in Section 3 has identified a number of significant issues that could affect the regulatory acceptance of SMR designs submitted for GDA.

For each issue a recommendation has been made on actions that could be taken to facilitate regulatory acceptance of an SMR design. The main issues and the recommended actions arising from the study are summarised below:

4.1 Classification and diversity requirements placed on protection systems

The UK approach to treating design-basis faults and hazards results in requirements for classification and diversity of protection systems that go beyond those in other jurisdictions. These requirements have resulted in significant changes being made to the designs of the large reactors previously submitted to GDA. Similar requirements on an SMR design may have a proportionately larger economic impact due to the higher "cost-per-megawatt" because of the smaller plant output.

Should a requirement for plant design changes be indicated to meet the UK classification and diversity principles, it is recommended that the SMR vendor perform a holistic risk-informed cost-benefit ALARP analysis using probabilistic safety analysis (PSA) techniques, to justify that the cost and difficulty of the modification was justified by the reduction in risk achieved. In such a PSA analysis it is recommended that the assumed reliability of plant items against common cause failure (CCF) should be modeled using state-of the art CCF methods such the USNRC CCF methodology.

If the SMR vendor concludes that that a particular design enhancement is not ALARP for their particular plant, the onus is on the vendor to make the safety case to the regulator. Our interactions with the regulator lead us to the view that the regulator is very open to such discussions.

4.2 Inspection of High Integrity Components

For the large reactors previously submitted to GDA, the UK regulator has asked for more diverse and extensive inspections of critical 'high integrity' parts of the pressure boundary than are required in other jurisdictions. Implementing these additional manufacturing and in-service inspections on smaller plants could have a greater economic impact (there will be fewer megawatts over which to share the significant recurring costs), and perhaps be even more difficult given the very compact designs, which may not allow access for inspection by current techniques.

It is recommended that an SMR developer takes full account of specific UK inspection requirements an early stage of an SMR design development process by identifying the components and welds that are to be classified as high integrity components, together with the inspection method that will be applied, taking account of access constraints.

The United Kingdom over the last several decades has been a leader in the development of "non-destructive examination" techniques, designed to detect defects in pressure boundary components. Research has both improved the ability to detect defects in complex geometries, and has also resulted in development of "condition monitoring" techniques that allow semi-continuous and remote assessment of components. This research has been resulted in effective commercialization of advanced techniques, and widespread use, for example in LNG applications.

It is therefore recommended that consideration be given to initiating a significant research programme in the non-destructive examination area, capitalizing on the existing UK expertise. The methods development, and indeed the performing of the inspections, is a high value-added activity, where the United Kingdom could both contribute and benefit significantly.

4.3 Use of software-based control and instrumentation (C&I) systems

A reluctance to rely solely on programmable, software-based, instrumentation and control systems for nuclear safety applications is probably more pronounced in the United Kingdom regulatory regime than in other jurisdictions. Such systems are also subject to more stringent qualification and testing requirements than applied outside UK. These requirements have led to extensive design modifications for large reactors previously submitted for GDA including provision of new non-programmable back-up systems for digital control and instrumentation systems. Similar requirement for SMRs could be proportionately more troublesome due to higher 'cost per megawatt' of plant modifications.

To assist in the regulatory acceptance of the software based control and instrumentation systems used in SMRs, it is recommended that a research programme is initiated aimed at advancing the general areas of formal software specification, design and testing, with the objective of raising the general level of confidence in the use of software in safety critical systems in nuclear applications. This would indeed have benefits that go well beyond just the nuclear sphere. It would also build on, and foster, a good base of expertise in the UK.

In the shorter term, it is further recommended that a complementary research program be initiated to identify and understand the way in which software is used in safety critical applications outside the nuclear sector, along with an assessment of how such usage could be mapped across into the nuclear sphere.

4.4 Need for adequate safety and environmental case and frozen reference design

A fundamental requirement for GDA of a new-build reactor is that Requesting Parties provide a comprehensive safety and environmental submission linked to a 'frozen' reference design for the systems, structures and components that are important to nuclear safety. Changes to the reference design made during GDA must be controlled by a defined change management procedure. Lack of a defined reference design and a clear safety and environmental case was considered by the regulators to have been a significant impediment to completion of GDAs of large reactors.

The detailed designs and safety cases for the SMRs are less advanced than those of the plants submitted to previous GDAs so it is expected that their design and safety and environmental documentation may need significant further development to reach the level of detail expected.

To minimise delays in GDA acceptance it is recommended that that requirement to provide a frozen and well documented reference plant design linked to a safety and environment case, and backed by a well defined design change control process, is identified to an SMR vendor as early as possible in the GDA process.

4.5 Validation of analysis methods for natural circulation cooling

Generically, the use of "passivity"; i.e. greater reliance on buoyancy-driven natural circulation flows to provide cooling, is almost ubiquitous in SMR designs. For some designs this extends to heat removal during normal operation, but for all designs it is relied upon to some degree under fault conditions.

This is understandable, as passive cooling does not rely on backup power in order to provide coolant circulation, greatly simplifying the plant design. However, making an acceptable safety case that adequate natural circulation cooling will take place is surprisingly difficult.

Building full-size replica plant to demonstrate the effectiveness of natural circulation would be ideal but is obviously out of the question. However, for deep technical reasons, making measurements on small-scale facilities and extrapolating is very difficult in this area. Developing computational tools to predict the behaviour is in principle possible, but it is very much at the frontier of current research in nuclear thermal hydraulics.

The above comments apply to PWR type SMRs, where the fluid circulating is liquid water. The predictive difficulties increase significantly if fault conditions are being considered, under which local boiling and thus steam generation may begin to take place, which markedly complicates the physical processes involved.

As demonstrating the effectiveness of natural circulation cooling would be fundamental to the GDA acceptance of SMR designs using passive cooling, it is considered that further research in this area could be beneficial for supporting an SMR programme. In the United Kingdom, there is a strong background in developing predictive methods for complex flows of this kind; indeed the field of computational fluid dynamics originated in the UK, and the UK remains a leader in this field. We therefore recommend that consideration be given to initiating a significant focused research program in this area. Such a programme, would provide data potentially useful for more than one SMR type, including non-PWR designs: it would need to combine an appropriate mix of suitable scale measurement facilities, in which relevant phenomena are studied on an economically achievable scale, with a parallel program of the development and validation of computational predictive methods for these flows.

4.6 Environmental issues

For all reactor types, GDA requires submission of a detailed environmental report providing an assessment of environmental discharges of radioactive and non-radioactive materials, and review of the controls and measures for the disposal of wastes generated by plant operations, including spent fuel. Generically there do not seem to be significant environmental issues associated with PWR-type SMRs that are more challenging than those faced by the large PWR type reactors previously submitted to GDA, none of which has presented significant difficulties.

For the non-PWR type SMRs identification and assessment of each of many discharge streams is likely to present significant challenges due to unfamiliarity of materials and due to their designs being insufficiently developed. It is also clear that designs using large quantities of irradiated lead, sodium and fissile salt, combined with as yet unknown trace elements, possibly prone to activation, will present significant challenges for environmental assessment and public acceptance.

It is recommended that for all SMRs the depth and scope of the environmental report required for a GDA is brought to the attention of a vendor at the start of the GDA process to minimise delays in achieving GDA acceptance. For the non-PWR reactor types early attention should be given to developing a design that achieves minimisation of environmental discharges and the generation of radioactive wastes, in accordance with the UK concept of applying Best Available Techniques for environmental optimisation.

4.7 Decommissioning

A GDA safety and environmental submission is required to consider all through-life aspects of a plant including eventual decommissioning of the power station. Whilst there will be differences in detail, there seems no reason to conclude that decommissioning of PWR-type SMRs will present fundamentally different challenges from decommissioning of larger PWRs, which do not appear to present significant difficulties.

Whilst there is some prior experience of liquid metal or molten salt cooled reactors, it seems inevitable that the decommissioning of such reactors will be far more challenging due to the materials used (large quantities of irradiated lead, or irradiated sodium, or irradiated salt), and the lack of familiarity with such materials in the UK nuclear sector. For example it may be easiest to remove these materials as liquids, which would involve keeping the part-decommissioned facility at high temperature, requiring a more complex safety and environmental case. It is recommended that if such designs are pursued, the requirement for a decommissioning strategy is brought to the attention of a vendor at the start of the GDA process to minimise delays in achieving GDA acceptance.

5 CONCLUSIONS

As part of a Techno-Economic Assessment of current SMR designs, a pre-GDA assessment has been performed to identify issues and challenges that could arise if an SMR was submitted to a GDA process, and to develop possible arguments by which they issues might be addressed.

To perform the pre-GDA assessment, published UK regulatory principles and guides and published reports on the outcome of GDAs for large reactors, were reviewed to identify issues likely to be raised by regulators in a GDA of an SMR. The list of potentially significant issues was validated at workshops and meetings held with the regulators themselves.

It is noted that although the SMRs have much lower outputs than the plants considered in previous GDAs, the design and safety requirements applied by the regulators would be similar to those applied in the GDAs of the larger plants.

The main issues identified in the assessment were as follows:

- UK classification and diversity requirements on the design of reactor protection systems could potentially result in significant changes being needed to current SMRs designs, potentially with a large economic impact. To address this issue it is recommended that an SMR vendor performs a cost-benefit analysis using probabilistic techniques, to confirm that an indicated plant modification meets the ALARP principle that risks should be are as low as reasonably practicable.
- UK requirements for inspection of 'high integrity components' could have a significant economic impact on an SMR programme due to the potentially high specific cost of recurring inspections, and difficulties with physical access to plant. To address this issue it is recommended that an SMR developer identifies the components and welds that are to be classified as high integrity components, and the inspection method that will be applied, at the start of a GDA, to establish the feasibility of the design. It is further recommended that UK research is initiated in the area of non-destructive examination, aimed at improving the ability to detect defects in complex geometries, and developing "condition monitoring" techniques for semi-continuous and remote assessment of components.
- UK requirements for the design, testing and application of software-based, instrumentation and control systems for nuclear safety purposes are likely to have a significant impact on the design of SMR control and instrumentation systems. To assist in the regulatory acceptance of software based control and instrumentation systems used in SMRs it is recommended that UK research is initiated in software specification, design and testing, with the aim of raising the general level of confidence in the use of software in safety critical systems in nuclear applications.
- Lack of a properly defined reference design that was clearly linked to the safety and environmental case was considered by the regulators to have been a significant impediment to completion of previous GDAs. To minimise delays in GDA acceptance of SMRs it is recommended that that the importance of a frozen, well documented, reference design, linked to a safety and environment case, is emphasised to an SMR vendor as the start of a GDA process.
- SMR designs generally rely on "passive" natural circulation cooling for heat removal in faults or in normal operation. Accurate prediction of natural circulation behaviour in complex geometries presents considerably technical difficulties, especially for conditions where local boiling is taking place. To help inform regulatory assessments of SMR safety submissions, it is recommended that a UK research programme is initiated to conduct tests on suitably scaled measurement facilities, and develop and validate predictive methods for natural circulation.

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