Office for Nuclear Regulation

ONR895

Independent Research into the Seismic Isolation of SMRs and AMRs

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ITER Tokamak Fusion Reactor, August 2014. Credit: @ITER Organization

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Executive Summary

Arup has been instructed by the Office for Nuclear Regulation (ONR) to conduct independent research into the application of seismic isolation on Small Modular Reactors (SMRs) and Advanced Modular Reactors (AMRs) in the UK. The aim of the research is to increase ONR's knowledge in the field of seismic isolation, such that ONR can carry out an independent, effective assessment of designs based on up-to-date information.

It is likely that new reactor designs in the UK, such as SMRs and AMRs, will incorporate seismic isolation to standardise the analysis, design, review and construction for a broader range of sites. Seismically isolated reactors have not been used on nuclear sites in the UK before and have had limited adoption internationally. One of the key considerations for regulatory assessment will therefore be the extent to which the Requesting Party (RP) demonstrates that Relevant Good Practice (RGP) has been established in the area of seismic isolation.

The scope of the research has been limited by ONR to cover elastomeric bearings as these are considered the most likely bearings to be proposed in the immediate term in the UK. The focus of the research has been on the Civil Engineering aspects of the design, testing, installation and maintenance of the Seismic Isolation System (SIS). The review of RGP has focused on published regulatory guidance and international codes and standards that are expected to be used for new reactor designs in the UK. This has primarily involved the European codes and standards for anti-seismic bearings and the US nuclear standards on seismic analysis.

This report includes discussion on aspects of the safety case, design, specification and testing, and installation, inspection and maintenance. The conclusions for what constitutes RGP within the UK context have been summarised as a set of expectations throughout the report. These are not intended to be prescriptive but to provide a benchmark for the potential approaches that are considered likely to satisfy the UK regulatory requirements.

In summary of this research, the following challenges are considered to be the most significant in assessing the safety case for the use of an SIS on a Nuclear Power Plant (NPP) in the UK:

- The Eurocode and Euronorms covering the design and testing of anti-seismic bearings are not nuclear specific so are expected to be supplemented and enhanced by the RP to achieve the required reliability. Based on typical nuclear practice in the UK, it is likely that this will be achieved by combining with the US nuclear standards which provide greater detail on the analysis requirements. However, the basis of the standards have significant differences and the compatibility of requirements must be justified. If US standards are adopted then particular care should be taken in ensuring compatibility.

- The Beyond Design Basis (BDB) hazard is not defined in UK regulatory guidance and the performance requirements of the bearings under BDB shaking are not captured in the European standards. It is expected that the approach for justifying the absence of cliff-edge effects under BDB shaking is developed by the RP.

- Elastomeric bearings are considered to have non-ductile failure modes and are not considered to fail in a safe manner. The use of a stop is one approach to prevent the failure of the bearings under excessive deformation. A stop has not been implemented in the precedent isolated nuclear facilities and there is limited guidance on how to consider the consequences of impact with the stop. The analysis and design approach for considering the effects of impact on the stop and supported Structure, System and Components (SSCs) will need to be developed by the RP.

- The performance of the isolated NPP under BDB shaking is expected to be considered as part of the Probabilistic Safety Analysis (PSA) and Severe Accident Analysis (SAA). The performance of the bearings beyond the tested parameters and the consequence of impact with a stop are strictly beyond the requirements for Civil Engineering and will be difficult to assess with any confidence. The RP should give further consideration of these issues for safety critical SSCs.

- Elastomeric bearings with synthetic rubber may exhibit a higher variability of mechanical properties than those with natural rubber. For this reason, synthetic rubber bearings are prohibited for use in nuclear

facilities in the US despite these being used on the precedent nuclear facilities in France. It is critical that the variability of the mechanical properties of the bearings is considered within the safety case of the SIS.

- The variability and reliability of the bearings should be appropriate for the safety classification of the facility and justified in the analysis and design methodology for the SIS. One approach adopted in the US is to limit the variability of the bearing properties to less than ±20% over the lifetime of the facility such that the variability may be considered insignificant, in comparison to that in the ground motion, soil and structure. Alternatively, the methodology for determining the Upper Bound Design Properties (UBDP) and Lower Bound Design Properties (LBDP) in the European bearing standards should be developed to achieve the required level of reliability. The seismic analysis methodology of the building and supported SSCs must consider the full range of potential properties to calculate the forces and displacements used for design.

- The European standards provide a more comprehensive testing regime for the bearings than the US standards, but additional requirements are expected for the use on nuclear facilities. The interpretation of the results in calculating the UBDP and LBDP must also be justified considering all mechanisms that may cause variability of the stiffness and damping.

- There are currently no methods for commissioning the dynamic behaviour of an SIS after installation and therefore a greater reliance is placed on the quality control measures on the production of individual bearings. It is expected that the frequency of factory production testing in the European standards is enhanced and justified based on the required reliability.

- The properties of elastomeric bearings may vary over time due to ageing of the rubber and there are known limitations with the results of accelerated ageing tests used to assess this effect. An in-service testing regime of full-scale sample bearings is therefore expected to be developed in addition to inspections and long-term monitoring. The results of the in-service testing should be compared with design assumptions and corrective action made if required.

- The introduction of seismic isolation will affect supported and surrounding SSCs and the consequences must be communicated with other disciplines. For example, additional verification will be required for the deformation capacity of SSCs crossing the isolation layer.

The proposed use of seismic isolation for SMRs and AMRs is currently driving research in this area and it is expected that alternative approaches for meeting RGP will be developed. The following topics of further research are therefore recommended for ONR to stay abreast of technical developments in this area:

- The compatibility of European and US codes and standards has been highlighted as a regulatory challenge for NPPs with seismic isolation but this is a common challenge when using RGP adopted from US requirements. Further research into the reliability basis of the European and US codes and standards would be expected to have a wider application beyond seismic isolation and is recommended for consideration.

- It is understood that the topical report on seismic isolation that is currently under development for the United States Nuclear Regulatory Commission (NRC) will propose a risk-based approach to define the performance and acceptance criteria based on the core damage risks of AMR technologies. This approach is expected to differ significantly from UK regulatory guidance and is expected to require cross-discipline consideration. It is recommended that ONR review this document when it becomes publicly available later this year.

- This research has focused on the seismic design of isolated NPPs but the introduction of seismic isolation will also affect the design to other external hazards such as radiation, fire, flooding, blast and aircraft impact. Limited guidance is available in the literature reviewed so it is recommended that a detailed review of the latest research is undertaken for these topics.

- It is not anticipated that vertical isolation will be proposed for regulatory assessment in the immediate future due to the significant challenges associated with rocking behaviour and lack of precedents even outside of the nuclear sector. Vertical isolation is more likely to be included on a component level but this level was beyond the scope of this research. Should vertical isolation be proposed on a future NPP in the UK it is recommended that ONR undertake a review of the latest research on this topic.

- It is recommended that ONR engage with the French regulator to discuss how the European standards have been enhanced for the recent nuclear facilities in France and whether there are elements which can be incorporated into UK regulatory guidance.

List of Abbreviations

ACI	American Concrete Institute
ALARP	As Low As Reasonably Practicable
AMR	Advanced Modular Reactor
ANT	Advanced Nuclear Technology
ASCE	American Society of Civil Engineers
BDB	Beyond Design Basis
BDBA	Beyond Design Basis Analysis
BDBE	Beyond Design Basis Earthquake
BE	Best Estimate
BS EN	British Standard Euronorm
CCF	Common Cause Failure
CR	Polychloroprene Rubber
CS	Clearance to the Stop
CSS	Curved Surface Slider
DBE	Design Basis Earthquake
ENEA	Energia Nucleare Energie Alternative
FIRS	Foundation Input Response Spectra
FPC	Factory Production Control
FSS	Flat Surface Slider
GDA	Generic Design Assessment
HDRB	High Damping Rubber Bearing
HTGR	High Temperature Gas-cooled Reactors
IAEA	International Atomic Energy Agency
JHR	Jules Horowitz Reactor
LB	Lower Bound
LBDP	Lower Bound Design Properties
LDRB	Low Damping Rubber Bearing
LFR	Lead-cooled Fast Reactors
LRB	Lead Rubber Bearing
LWR	Light Water Reactor
MSR	Molten Salt Reactor
NPP	Nuclear Power Plant
NR	Natural Rubber
NRC	United States Nuclear Regulatory Commission
ONR	Office for Nuclear Regulation
OPEX	Operating Experience
PPRB	Polymer Plugged Rubber Bearing
PSA	Probabilistic Safety Analysis
PWR	Pressurised Water Reactor
R&D	Research and Development
RG	Regulatory Guide
RGP	Relevant Good Practice
RP	Requesting Party
SAA	Severe Accident Analysis
SAP	Safety Assessment Principle
SDC	Seismic Design Category
SFR	Sodium-cooled Fast Reactor
SICDRS	Site-Independent Certified Design Response Spectra
SIS	Seismic Isolation System
SMR	Small Modular Reactor
SPRA	Seismic Probabilistic Risk Assessment
SSC	Structure, System and Component
SSI	Soil-Structure Interaction
TAG	Technical Assessment Guide

UB	Upper Bound
UBDP	Upper Bound Design Properties
US	United States

1. Introduction

Arup has been instructed to conduct independent research into the application of seismic isolation on Small Modular Reactors (SMRs) and Advanced Modular Reactors (AMRs) in the UK for the Office for Nuclear Regulation (ONR). The aim of the research is to increase ONR's knowledge in the field of seismic isolation, such that ONR can carry out an independent, effective assessment of designs based on up-to-date information.

1.1 UK context

It is likely that new reactor designs in the UK, such as SMRs and AMRs, will incorporate seismic isolation systems. These designs are likely to be subject to a Generic Design Assessment (GDA) to assess their suitability for construction and operation in multiple sites across the UK. During this assessment, and/or Site Licensing assessments, one of the key considerations will be the extent to which the Requesting Party (RP) or prospective licensee demonstrates that Relevant Good Practice (RGP) has been established in the area of seismic isolation.

Seismically isolated reactors have not been used on nuclear sites in the UK and have had limited adoption internationally. To support its independent regulatory decision making, ONR specialist inspectors require greater understanding of developing innovations and new technologies. The incorporation of seismic isolation into nuclear reactor designs is an area of focus.

1.2 Scope

The aim of this document is to inform ONR inspectors of the current RGP in the use of seismic isolation for nuclear facilities and to identify regulatory challenges and knowledge gaps.

The focus of the research has been on the Civil Engineering aspects relating to the design, testing, installation and maintenance of seismic bearings. Aspects of the design that are expected to affect other disciplines have been identified but not researched in detail.

The scope of this research has been limited to reviewing the likely seismic isolation systems which will be proposed in the immediate term within the UK market. These have been identified by ONR as:

- Low Damping Rubber Bearings (LDRBs)
- High Damping Rubber Bearings (HDRBs)
- Lead Rubber Bearings (LRBs) or Polymer Plugged Rubber Bearings (PPRBs)

The definition of LDRBs has been taken as elastomeric bearings made from both natural and synthetic rubber with an effective damping ratio of less than 6%, as defined in BS EN 15129 [25].

PPRBs are referenced in the European standards as elastomeric bearings with a plug of polymeric material to enhance damping. However, limited information on these devices is available and they are not understood to be used in practice. PPRBs have therefore not been considered further within this report.

Other types of bearings are mentioned in this report but have not been investigated in detail. Should other bearings be proposed to ONR then further research would be required.

The research has covered the codes and standards that are likely to be used for new reactor designs in the UK which ONR expects to be the European and US suite of standards. Other codes and standards exist that cover the design of seismic isolation but these have not been reviewed in detail.

Operational experience from existing isolated nuclear facilities has also been collated based on feedback from Nuvia and information provided in the IAEA TECDOC-1905 [7].

1.3 Methodology

The approach to the research has been to undertake a literature review of publicly available documents including regulatory guidance, codes and standards, and research papers. Operational experience has been obtained from Nuvia based on their work on existing isolated NPPs in France and South Africa.

It is noted that the majority of existing guidance is reflective of traditional large Light Water Reactors (LWRs) which may limit how existing regulation and guidance can be applied to SMRs and AMRs. This is due to the risk profiles associated with different technologies which form the basis of the assumptions in the codes and standards. AMRs are also expected to have significant design features such as deep embedment, isolation of individual components, integrated modules and vertical isolation systems which are not found on LWRs. This document aims to identify where guidance needs to be updated to account for different attributes.

1.3.1 Reference information

The ONR Safety Assessment Principles (SAPs) [1] have been used to frame the regulatory requirements for the Seismic Isolation System (SIS). The SAPs considered to be most relevant have been identified and discussed throughout the document and are listed in full in Appendix A. The Technical Assessment Guide (TAG) for External Hazards TAG-13 [2] and Civil Engineering TAG-17 [3] have also been reviewed. These include guidance on the seismic hazard but do not include specific requirements for seismic isolation.

Information published by international regulatory bodies has also been reviewed with primary references from the US included below:

- United States Nuclear Regulatory Commission, *Technical Considerations for Seismic Isolation of Nuclear Facilities*, NUREG/CR-7253, 2019 [11]
- United States Nuclear Regulatory Commission, *Seismic Isolation of Nuclear Power Plants Using Elastomeric Bearings*, NUREG/CR-7255, 2019 [12]
- International Atomic Energy Agency, *Seismic Isolation Systems for Nuclear Installations*, TECDOC-1905, 2020 [7]
- Kammerer, A., Whittaker, A., and Coleman, J., Regulatory gaps and challenges for licensing advanced reactors using seismic isolation, *INL Report INL/EXT-15-36945 Revision 0*, Idaho National Laboratory, 2016 [38]

The suite of Eurocodes and Euronorms relevant to seismic isolation were reviewed, incorporating the findings from the ENEA review study [6]. It is recognised that the Eurocodes and Euronorms are not considered RGP for nuclear design in the UK, but are often referenced in conjunction with US standards or enhanced by project specific specifications. Our review has focused on the main European seismic structural design standard, BS EN 1998-1 [23], the European product standard for anti-seismic devices, BS EN 15129 [25], and the suite of standards for structural bearings, BS EN 1337 [17].

The suite of relevant US standards and guidelines were reviewed, including ASCE 4-16 [29] and ASCE 43-19 [28]. We note that there is no US product standard for seismic isolation devices, equivalent to BS EN 15129.

It is understood that the US standards were written primarily for the US Department of Energy and have not been adopted by the US Nuclear Regulatory Commission (NRC). The NUREG/CR reports listed above were written by contractors to provide supporting information but do not constitute regulatory guidance. The Kammerer et al. paper refers to a draft seismic isolation NUREG but it is understood that this will not be published. Instead, a topical report that will provide guidelines on the seismic isolation of nuclear facilities is currently under development for submission to the NRC. This is expected to address SMRs and AMRs specifically and propose performance criteria and design considerations within the US context. The contents of the topical report are expected to include a discussion of existing US and international guidance, a risk-informed approach to setting performance criteria for AMRs, and design, manufacturing and operational considerations. The authors are requesting that the NRC endorse sections of the report related to the analysis, design and delivery of an SIS which are expected to differ from the requirements in the existing US standards. The report will include data and recommendations to support future editions of ASCE 4-16 and

ASCE 43-19 but there is no confirmed schedule for their update. The topical report was not available for review as part of this research and should be considered as part of future assessments.

Information on proposed SMR and AMR technologies has been gathered from publicly available sources. Very limited information is available on the proposed design and details of seismic isolation so specific issues are based on our understanding of the technologies.

1.3.2 Expectations

The design methodologies that are considered to meet RGP have been summarised throughout the document as a series of expectations that RPs should meet in their design submissions. This concept was developed with ONR on a previous GDA as a way to benchmark the potential approaches that are considered to achieve the regulatory requirements. The expectations focus on aspects that are novel to isolated facilities and do not include those that are the same for non-isolated facilities. A summary of the expectations is provided in Section 7.

It should be noted that specific design methodologies will still be subject to ONR assessment and the RP meeting the expectations in this document should not be considered a guaranteed method of achieving regulatory approval.

1.4 Research team

This research has been led by Arup who was responsible for the document review and drafting of the report. Specialist input has been provided by Nuvia based on their experience of designing, testing and installing seismic bearings on existing NPPs. The first draft of the report was subject to an independent peer review which was undertaken by Professor Andrew Whittaker who is leading research on seismic isolation within the nuclear sector in the US. Some comments highlighted the expected changes in future US guidance which is not considered to represent current RGP so could not always be closed out. The report was subsequently updated addressing the comments that were relevant to the UK regulatory regime.

2. Background

2.1 Seismic isolation

The intention of seismic isolation is to reduce the seismic demand on the superstructure and increase the operational resilience of the building. For NPPs, seismic isolation is typically proposed to reduce the seismic demand for the Design Basis Earthquake (DBE) but it introduces additional considerations for the performance at higher levels of shaking.

The use of seismic isolation is well established across the built environment in conventional buildings, bridges and industrial structures, but their use in the nuclear context is much more limited, with only a handful of precedent nuclear facilities in France and South Africa. Seismic isolation has not been implemented on an existing NPP in the UK.

2.1.1 Horizontal isolation

Seismic isolation is achieved through installation of a flexible layer at the base of the facility which increases the fundamental period (reduces the fundamental frequency) of the response and reduces the seismic accelerations transmitted from the ground to the superstructure. Total seismic displacement is increased, but this displacement is mostly concentrated across the isolation layer, is mitigated by the provision of energy dissipation in the isolation system, and the storey drifts of the superstructure are reduced. The isolation system typically provides a stiff load path for gravity loads which makes it more difficult to achieve seismic isolation in the vertical direction.

Figure 1 shows a typical cross-section of an isolated NPP, similar to those constructed in France and South Africa. The terminology for the different components of the structural system will be used throughout this report.

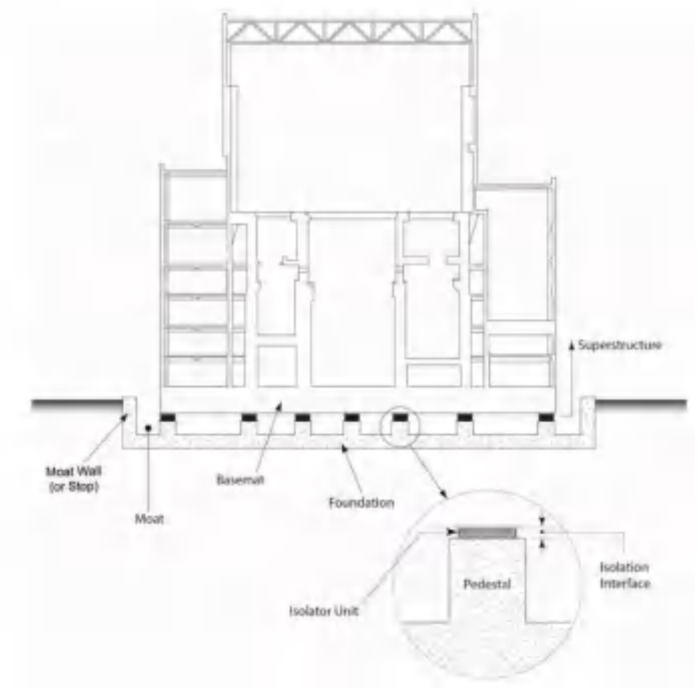

Figure 1 Cross-section of a seismically isolated NPP nuclear island structure [29]

2.1.2 Vertical isolation

Seismic isolation of buildings in the vertical direction is difficult to achieve as the isolation system typically has a stiff load path for gravity loads. However, vertical seismic effects are generally less critical for structures as the demand may be accommodated within load factors on gravity loads and special consideration is generally only required for more flexible components such as long-spans, cantilevers and transfer structures. If required, vertical isolation can be implemented on a component level instead.

Vertical isolation of the entire facility has been proposed on some NPPs through the introduction of devices with controlled dynamic stiffness in all three directions [7]. Research undertaken on vertical and three-dimensional isolation systems in nuclear structures investigated a number of different systems including those consisting of large helical steel springs, air springs, cable reinforced air springs, hydraulic systems or coned disc springs [48].

The following challenges accompany the introduction of vertical isolation:

- Vertical load carrying capability both before, during and after an event.
- Vertical stiffness during normal operating conditions and during an event.
- Interaction with the horizontal isolation and/or rocking effects (rocking may not be acceptable for SSCs within the facility). Rocking can increase horizontal accelerations at the upper levels of the isolated superstructure.
- Increased complexity of flexible connections for SSCs crossing the isolation layer.
- Qualification of an SIS with increased complexity.
- Safety requirements and reliability of semi-active systems.

There are currently no NPPs with vertical or 3D isolation systems [48] however it is expected that Research and Development (R&D) will continue to be undertaken to develop these systems. It is not expected that this technology will be proposed for regulatory assessment in the UK in the immediate future so a detailed review of this has not been undertaken.

2.2 Reactor types

A detailed history of isolated nuclear and non-nuclear structures is provided in NUREG/CR-7253 [11] including a description of the type of isolation employed on the two existing isolated NPPs and the two isolated nuclear facilities that are currently under construction.

The existing isolated NPPs and nuclear facilities under construction are listed below:

- Cruas NPP, France (4 reactors)
- Koeberg NPP, South Africa (2 reactors)
- ITER, France (tokamak fusion reactor)
- Jules Horowitz Reactor (JHR), France (material test reactor)

It is noted that the safety requirements for the proposed SMRs and AMRs are expected to differ from both the precedent NPPs and the R&D reactors. All six of the reactors across Cruas and Koeberg are large Pressurized Water Reactor (PWR) units and were constructed in the 1980s. Nuclear regulations, codes and standards have developed in this time and advanced reactor technologies will have different safety requirements. ITER and JHR are both R&D reactors and, while the designs used modern codes and standards, they may not satisfy the safety and reliability requirements for an NPP. It is therefore important to consider these differences when assessing the OPEX from these facilities.

2.2.1 SMRs

SMRs are categorised by IAEA as reactors with capacity up to 300MWe, approximately one third of the size of traditional reactor types. This is, however, a loosely applied categorisation, noting the Rolls Royce SMR is 470MWe. For the purpose of this research, ONR has limited SMRs to conventional LWR technologies with AMRs capturing all other reactor technologies.

There are currently no SMRs in operation or under construction in the UK and no land-based SMRs operational in the world.

The design of SMRs is expected to utilise a modular, or generic design approach, to enable efficiencies in design and implementation of these smaller reactors. It is expected that seismic isolation will enable the

GDA for SMRs to further standardise the analysis, design, review and construction for a broader range of site types and hazards [11].

The GDA as a precursor to licensing in the UK is similar to the US approach. The US approach aims to certify the superstructure NPP design using a certified seismic design response spectrum (CSDRS) to undertake the design and detailing. This is similar to a generic design spectrum used in the UK GDA. However, unlike the CSDRS, the generic design spectrum is not prescribed by ONR. The design of the NPP in the US then requires a site-specific isolation system and foundation to reduce transmitted accelerations to below the CSDRS for the facility to meet the certified requirements.

It is expected that the seismic hazard used at GDA will bound the anticipated site-specific characteristics to enable the generic design to be applied to a number of different deployment sites. It is therefore anticipated that the seismic isolation system (SIS) may also be part of the GDA in the UK with only minor modifications required to account for extreme hazard or soil conditions [4].

The industries' intent for SMR designs is to be simpler and rely more on passive systems and inherent safety characteristics of the reactors to provide additional margin to failure and improve safety compared with traditional reactors. The SIS forms a part of the passive protection for facilities against seismic hazard.

The key differences between SMRs and traditional large reactors which may impact the design of the SIS are:

- How deep embedment affects the design, analysis and cost benefits.
- The aspect ratio of SMRs differ from traditional LWRs affecting the response of the isolators.
- The density of coolants, effect on sloshing in pools and pressurised vessels, and impact on the fuel rods.
- The size of functional containment for integrated systems as opposed to non-integrated systems which effectively house the reactor only.

An example of a proposed SMR with an integrated system is by NuScale Power in the US utilising PWR technology. As can be seen in Figure 2, this design has a large reactor pool that differentiates it from the traditional NPP shown in Figure 1 and will require significant additional consideration of the secondary effects of the pool and the support positions, and behaviour of the multiple tall slender integrated reactor vessels.

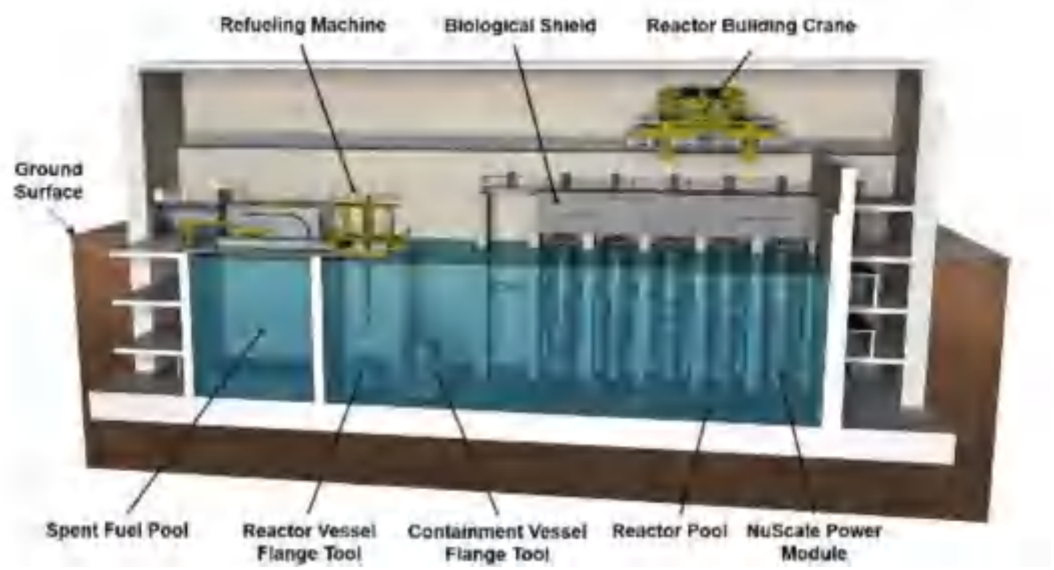

Figure 2 Cut-away view of NuScale power plant, an example of an integrated PWR [8]

2.2.2 AMRs

For the purpose of this research, ONR has defined AMRs as all reactor technologies other than LWRs. Some AMR technologies are already operational worldwide including High Temperature Gas-cooled Reactors (HTGRs) and Sodium-cooled Fast Reactors (SFRs). Others are more emerging technologies which are not yet operational worldwide including Molten Salt Reactors (MSRs) and Lead-cooled Fast Reactors (LFRs). These use heavier coolants which may affect the load distribution and sloshing effects. AMRs are expected to take advantage of the same modular construction principles and seismic isolation as SMRs but are at an earlier stage of development.

2.3 Deep embedment

Deep embedment is a feature of some SMR and AMR proposals and poses challenges for the seismic analysis and design of the facility. Kammerer et al. [38] state that deeply embedded reactor buildings are unlikely to be seismically isolated due to the excavation and additional cost which will likely outweigh the benefits of reducing seismic demand. Instead, safety related components such as the reactor vessel may be isolated separately at a component level. The seismic isolation of equipment is beyond the scope of this research.

An example of an AMR proposal with deep embedment is the HTTR in Japan as shown in Figure 3. This is not proposed to be seismically isolated. The reactor is embedded five storeys (approximately 25–30m) below ground with two taller storeys (approximately 20–25m) above ground.

Figure 3 Cut-away of HTTR showing deep embedment of an AMR [8]

3. Safety case

3.1 Safety classification

SAP ECS.2 [1] requires SSCs that deliver safety functions to be identified and classified based on the safety functions and their significance to safety. Considering the SIS as an SSC, the safety classification must be set considering all of the following:

- The category of safety function to be performed by the SIS.
- The probability that the SIS will be called upon to perform the safety function.
- The potential for a failure to initiate a fault or to affect the performance of another SSC.
- The time following any initiating fault at which it will need to operate to bring the facility to a stable and safe state.

SAP ECE.1 [1] requires that the performance and safety function of civil engineering structures, including the SIS should be specified. The purpose of the SIS is to limit the seismic demand to the superstructure while providing a robust horizontal and vertical load path for the supported SSCs to the foundation under both operational and accidental conditions. Although various conditions are discussed later in this section, the most critical condition is likely to be under seismic actions where the potential for failure is higher and could lead to damage of the supported SSCs.

The recommended categorisation scheme requires an SSC to be classified as either Class 1, 2 or 3 based on its role in fulfilling a safety function that is significant to nuclear safety.

Given the intent of the SIS is to provide seismic protection to other SSCs, it is anticipated that a SIS that supports safety critical SSCs is defined as a Class 1 SSC; i.e. forms a principal means of fulfilling a Category A safety function. As the failure of the SIS would constitute a change in design envelope and escalation of risk of failure to the reactor then it would be unlikely to be appropriate for it to be assigned a lower Class. However, lesser Classes may be applicable if a SIS is adopted to support less safety critical SSCs.

The US classifies SSCs based on a function of the Seismic Probabilistic Risk Assessment (SPRA), which is reactor and power-rating specific [38]. Therefore, different target demands will be implemented on different facilities in the US based on the facility or reactor type. The US standards require each SSC to be assigned a Limit State and Seismic Design Category (SDC) to describe the acceptable level of damage and annual frequency of exceeding the performance level, as outlined in ANS 2.26 [5]. Structures within the nuclear island of large LWRs are typically assigned the highest categories of Limit State D (essentially elastic behaviour) and SDC-5. It is understood that lower categories may be justified for some AMRs based on their passive safety features and atmospheric operating pressures. No guidance is provided for the classification of an SIS; however, it is considered reasonable to assign the SIS the highest classification used for the supported SSCs.

Once the safety class of the SIS is established, corresponding design requirements should be specified and applied. This should take into consideration that the SIS is formed of multiple bearings and the design requirements for the system should be distinguished from the design requirements of individual components. As recommended in IAEA guidance [9], the design requirements applied at the system level may include the single failure criteria, independence of redundancies, diversity and testability. These requirements are considered to demonstrate the reliability of the system as a whole and are discussed further in Section 3.3. The design requirements applied for individual components are typically expressed by specifying the codes or standards that apply and will include component level testing. It is worth noting that system level requirements may not always be included in codes and standards.

Expectations:	
3.1-1	The safety classification of the SIS should consider the potential of failure to affect the performance and safety function of the supported SSCs. It is expected that the safety classification will be the highest classification used for the supported SSCs.

3.2 Codes and standards

SAP ECS.3 [1] requires that the design of SSCs that are important to safety should be in accordance with appropriate codes and standards. The primary codes and standards we anticipate being used in the design and installation of a SIS on a nuclear application are listed below.

- European standards:
  - BS EN 1998-1:2004 Eurocode 8 Design of structures for earthquake resistance. [23]

    BS EN 1998-1 is the seismic standard in Europe and summarises general seismic design requirements for structures, and specific requirements for buildings. Additional requirements and guidance on the seismic hazard are found in the SAPs [1] and TAG-13 [2] provided by ONR.

  - BS EN 15129:2018 Anti-seismic Bearings. [25]

    BS EN 15129 is a standard for anti-seismic bearings and includes requirements for their reliability, performance, and testing.

  - BS EN 1337-1:2000 Structural Bearings. [17]

    BS EN 1337 is formed of 11 parts and summarises the requirements for the design, protection, inspection, maintenance, transport, storage, and installation of a range of different types of structural bearings including elastomeric bearings. These bearings are for transmitting forces between the structure and support and not only for seismic applications. Part 3, Elastomeric Bearings [18], is the most relevant for the bearings discussed in this report and includes details on elastomer materials and the testing standards to characterise bearing behaviour.

- US standards:
  - ASCE 43:2019 Seismic Design Criteria for Structure, Systems, and Components in Nuclear Facilities. [28]

    ASCE 43-19 is a standard for the seismic design criteria for SSCs in nuclear facilities. Chapter 9 addresses seismically isolated structures. Previous versions have been used as RGP on NPPs in the UK.

  - ASCE 4:2016 Seismic Analysis of Safety-Related Nuclear Structures. [29]

    ASCE 4-16 is a standard for the seismic analysis of nuclear facilities. Chapter 12 addresses seismically isolated structures and is identical to Chapter 9 of ASCE 43-19.

The second generation of Eurocodes is currently under development and will include an update to both BS EN 1998 and the associated Euronorm BS EN 15129. The draft BS EN 1998 has been reviewed as part of this research; it was not possible to obtain the draft of BS EN 15129. The codes and standards should reflect the functional reliability requirements of the SSCs and it is preferable that they are nuclear-specific or, as a minimum, non-contradictory with nuclear requirements. Nuclear facilities are beyond the scope of the European standards listed above so, while they contain engineering principles that are relevant to nuclear facilities, the requirements are expected to be modified or enhanced to ensure they provide the level of reliability and performance expectations commensurate with the safety function being delivered.

In the absence of nuclear-specific European standards, it is expected that the US standards will be used as a basis to enhance the European standards, providing the requirements needed to achieve the reliability needed for nuclear facilities. However, the SAPs [1] recommend against combining standards so the compatibility of international standards will need to be demonstrated and justified through validation and verification.

It is noted that the codes and standards listed above provide design requirements at a component level and do not provide guidance for assessing the risk at a system level. Additional guidance for considering the system level performance must therefore be used which should preferably be nuclear-specific.

Expectations:	
3.2-1	In the absence of a standard for the seismic design of nuclear facilities in the UK, it is expected that requirements are modified or enhanced to achieve the reliability required, or alternative nuclear-specific standards are used.
3.2-2	ASCE 43-19 and ASCE 4-16 are considered to be RGP for the seismic design of nuclear facilities and it is expected that they will be used to inform nuclear specific requirements and modifications for the analysis and design of the SIS.

3.3 Design for reliability

SAP EDR.1 [1] requires that SSCs are designed to be inherently safe, or to fail in a safe manner, and that potential failure modes should be identified. Failure of the SIS may be interpreted differently, since a reduction in horizontal capacity may not be considered failure provided the vertical capacity is maintained. It is noted that the performance expectations in ASCE 4-16 [29] state that bearing damage is acceptable under the Beyond Design Basis Earthquake (BDBE) but the load-carrying capacity must be maintained. For the purpose of this report, failure has been interpreted as a reduction of horizontal or vertical capacity and the consequences of each are discussed further below.

For the components of the SIS, the potential failure modes are expected to include the following:

- Excessive displacement of elastomeric bearings leading to delamination of the bearing or rubber failure due to shear.
- Buckling of bearings under combined vertical loads and horizontal drift.
- Excessive compression in the isolator causing shear-compression failure of the rubber or degradation of the contact surfaces.
- Excessive tension in the isolator causing shear-tension failure of the rubber or degradation of the contact surfaces.
- Loss of bearing capacity due to external hazards such as fire or internal hazards such as radiation.
- Failure of the connection between the bearing and pedestal due to excessive shear demand.
- Pedestal failure due to excessive shear demand.

The potential consequences of these failure modes are expected to include the following:

- Loss of vertical support to the superstructure.
- Excessive displacements that could lead to pounding of the superstructure with the surrounding substructure.
- Excessive displacements causing exceedance of the design envelope for SSCs crossing the isolation interface.

Some of the failure modes of the bearings exhibit low ductility and a sudden loss of capacity, such as buckling instability. However, other failure modes, such as delamination, may be considered more acceptable as the vertical load-bearing capacity of the bearings is maintained. Insufficient evidence is available to conclude that the failure of elastomeric bearings can be considered ductile and it is noted that they are rarely tested to failure. It may be possible to demonstrate that the potential failure modes in a particular design are ductile and considered to develop in a safe manner but since this is not reflected in current RGP alternative strategies are expected.

One strategy for mitigating the risk of bearing failure is to ensure there is a sufficient margin between the bearing displacements caused by design basis loading and the failure displacement. However, given the practical difficulty of assessing the failure capacity of elastomeric bearings it is considered difficult to quantify the margin. A risk-based approach may be more appropriate which would integrate the uncertainty in both the seismic hazard and structural response into a single calculation. This is currently under development in the US but is not covered by current RGP. SAP EDR.2 [1] requires that redundancy, diversity and segregation are incorporated in the design of SSCs, SAP ECE.2 [1] requires that a diverse and independent arguments are used in the safety case, and SAP EDR.3 [1] requires that a common cause failure (CCF) is explicitly addressed. A building-wide SIS is made up of multiple bearings and it could be argued that, in aggregate, the system has a significant level of redundancy. However, since the SIS is composed of similar bearings acting in parallel and each subjected to similar lateral deformation simultaneously [11], the chance of multiple bearings failing at the same time is correlated. It is therefore difficult to justify redundancy or demonstrate that the bearings are not susceptible to a CCF. An alternative strategy for mitigating the risk of bearing failure is to introduce a stop within the verified displacement range of the bearings. This approach is adopted in the US standard ASCE 43-19 [28] which requires the implementation of a stop at the BDBE displacement. This is intended to prevent the bearings from failing under shear strain and allows an alternative, more reliable, failure sequence for the supported SSCs. However, potential cliff-edge effects caused by the impact may need to be considered for the supported safety critical SSCs as discussed further in Section 3.5. The design implications of introducing a stop are discussed further in Section 4.5.

It is understood that the precedent nuclear facilities in France have not considered the use of an explicit stop but some have considered the loss of a single bearing as part of the design.

SAP EDR.4 [1] requires that no single random failure in a system should prevent the performance of its safety function. For the SIS, this is interpreted as its ability to maintain the vertical and horizontal load paths for supported SSCs with the loss of a single bearing. NUREG/CR-7253 [11] also recommends that the failure of one or even several bearings should be demonstrated to not significantly compromise the SIS to build further confidence in its reliability. The requirements for bearing loss are interpreted differently for the vertical and horizontal load paths as it is expected that elastomeric bearings can maintain their load-carrying capacity even if they have sustained damage under horizontal deformation [29]. It is therefore considered less likely that multiple bearings would be lost in the vertical load path than in the horizontal load path. This is discussed further for the design of the basemat in Section 4.7.2. (The requirement to consider the loss of a single bearing on vertical load path also provides confidence that the isolation system can perform adequately if an earthquake were to occur during bearing replacement.)

Expectations:	
3.3-1	The potential failure modes of the SIS must be identified and the consequences of failure assessed to demonstrate that it can fail in a safe manner. It is considered difficult to demonstrate this by providing sufficient margin so alternative strategies are expected to be considered.
3.3-2	The use of a stop is one approach to mitigate the risk of failure of the bearings and allow alternative failure sequences to be designed. Potential cliff-edge effects associated with impact should be considered in the PSA and SAA.
3.3-3	The design of the SIS should consider the loss of one or more bearings for the horizontal load path and the loss of a single bearing for the vertical load path.

3.4 Reliability claims

SAP ERL.1 [1] requires that the reliability claimed for any SSC takes into account its novelty, experience relevant to its proposed environment, and uncertainties in operating and fault conditions; SAP ERL.2 [1] requires that the measures to achieve reliability are stated. Given that the use of seismic isolation is relatively novel for nuclear applications, the lack of nuclear-specific codes and standards in the UK, and the lack of resilience to a CCF, it is expected that the approach to achieve the required level of reliability in the SIS is clearly outlined.

The approach to demonstrating reliability differs between the European and US codes and standards. While both employ deterministic design procedures, the US nuclear standards have been calibrated to achieve performance targets. This is significant when combining codes and ensuring compatibility of requirements. This section aims to discuss the differences between the approaches but does not claim to reach a conclusion on how best to demonstrate the required reliability for the SIS.

The differences between the seismic design procedures in different codes and standards are discussed in NUREG/CR-7253 [11]. The European standards calculate structural demands for a chosen intensity of shaking and check that the component capacity is greater than the demand. The US nuclear standards define both a frequency of earthquake shaking and a frequency of unacceptable performance for a particular building. Instead of using demand-capacity ratios a risk reduction factor is defined as the ratio between the frequency of exceeding a designated hazard and frequency of unacceptable performance for the structure or element.

The design basis seismic hazard for nuclear facilities in the UK is defined in TAG-13 [2] and SAP EHA.4 [1] as an annual frequency of exceedance of 10^{-4}. The demands for the design of the bearings are increased by both a reliability factor defined in BS EN 1998-1 [23] and a partial factor in BS EN 15129 [25]. It should be noted that these factors are intended to be applied to the lower hazard level defined in BS EN 1998-1.

BS EN 1998-1 cl. 10.3 requires an increased reliability for isolation devices by applying a magnification factor on seismic displacements. The recommended value of the magnification factor for buildings is 1.2 (and 1.5 for bridges) in the current version of the standard. The draft version of the standard recommends this value is increased to 1.5 for buildings, but that it can be reduced to 1.2 if specific analyses accounting for seismically active fault vicinity are used in the design [24]. The requirement for the magnification factor is consistent with the earlier discussion on redundancy although the reason is not explicit. The use of a single factor is considered to be overly simplistic for the application to nuclear facilities and additional justification would be expected to explain the purpose of the factor and demonstrate that the value chosen is appropriate.

BS EN 15129 requires a partial factor to be applied on seismic displacements in addition to the reliability factor in BS EN 1998-1. The value of the partial factor for elastomeric bearings is 1.15 so the combined effect on the seismic displacements is an increase of 1.5 x 1.15 = 1.725. These factors are required regardless of how the analysis results are post-processed to obtain design seismic displacements.

While the Eurocodes are not intended for use on nuclear applications, our understanding is that the resistance factors used to address uncertainty in structural demand are widely considered to be acceptable. The basis of the structural reliability is outlined in BS EN 1990 [22] which states that partial factors used to calculate characteristic values for material properties in the Eurocodes are associated with a 95% confidence level (i.e. 5th percentile values). It also indicates that where upper and lower bound properties are established directly, the properties should achieve an equivalent level of reliability, but provides limited guidance on the approach that should be used. The approach for determining the upper and lower bound properties of seismic bearings from test results is described in the Euronorm BS EN 15129 and is discussed in more detail in Section 4.3.2. However, the approach does not appear to have been calibrated to achieve the same confidence level as in BS EN 1990. It is therefore expected that the confidence level of the upper and lower bound properties is calculated to ensure the level of reliability is satisfactory.

In the US nuclear standards, the SDC defines the frequency of unacceptable performance for a particular building, called the "target performance goal", which determines the return period of the DBE. The intent of the design standards is then to achieve a 1% or smaller annual frequency of unacceptable performance for the DBE shaking. Underpinning this are the assumptions that the analysis procedures in ASCE 4-16 [29] predict seismic demands for DBE shaking at the 80th percentile level and that the equations for design strength in material standards, such as ACI 349-13 [27], deliver capacities at the 98th percentile exceedance probability. The performance expectations for seismically isolated buildings are summarised in ASCE 4-16 Table 12-1 and are consistent with these assumptions. Seismic demands for DBE shaking shall be calculated at the 80th percentile level, as discussed further in Section 4.1.1, and the superstructure shall achieve a 98% probability that demands will not be exceeded.

It is understood that new US guidance will place a greater emphasis on risk-based approaches to demonstrate that the target performance goal is achieved rather than relying on the assumptions in ASCE 4-16. These assumptions may not be valid for AMRs which are also considered to be lower risk technologies. Yu et. al. [47] introduce a risk-based approach that can be used to achieve a seismic risk target for a SIS. However, this type of approach is considered beyond the scope of this research as it is a significant departure from the current regulatory approach in the UK. Regardless of the codes and standards used, it is expected that the probability of unacceptable performance or reliability level is calculated for the design of all SSCs including the SIS and demonstrated that this meets the requirements of the safety case. If the US standards are used in combination with the European codes then the assessment of reliability must consider the differing basis of each code.

Expectations:	
3.4-1	The reliability level or probability of unacceptable performance should be calculated for the SIS and demonstrated that this meets the requirements of the safety case.
3.4-2	The reliability basis of different codes and standards must be considered when combining or enhancing requirements.

3.5 Beyond design basis

The principal hazard for the design of the SIS is earthquakes and the design basis seismic hazard for nuclear facilities in the UK is defined in TAG-13 [2]. SAP EHA.18 [1] requires analysis of beyond design basis (BDB) hazards but does not define a specific hazard level. TAG-13 states that if a single BDB event is selected, an annual frequency of exceedance of 10^{-5} is a reasonable starting point and notes that a 40% increase on the design basis has been employed in the past. The approach to BDB assessment is more prescriptive in ASCE 43-19 [28] which defines the BDBE as 150% of DBE. For clarity, the acronym BDBE will only be used in this report to refer to the definition in ASCE 43-19 and BDB shaking will be used to cover any event beyond the DBE.

In addition to SAP EHA.18, SAP EHA.7 requires that a small change in the design basis assumptions should not lead to a disproportionate increase in radiological consequences. The beyond design basis analysis (BDBA) should therefore confirm the absence of cliff-edge effects and establish the beyond design basis margin, i.e. the hazard level at which safety functions could be lost. The Civil Engineering design may therefore allow damage to occur under BDB shaking provided there is an absence of cliff-edge effects. The performance requirements in ASCE 43-19 are specified as a 90% probability that superstructure component capacities will not be exceeded and a 90% probability that the SIS will not lose gravity load-bearing capacity under the BDBE. Bearing damage is acceptable provided the load-carrying capacity is maintained. There is no requirement to test the bearings to failure to establish a margin but, as discussed in Section 3.3, the standard requires the introduction of a stop with the clearance being no less than the 90th percentile seismic displacements under the BDBE. This reduces the risk of bearing failure so seems reasonable to reduce the requirement to establish a margin to failure.

For the European standards, the application of the reliability factor and partial factor to the design basis seismic displacements (discussed in Section 3.4) could be considered as providing a degree of margin against BDB shaking. However, this does not appear to be the intent of the standard but rather to increase the reliability of a non-redundant system. It is therefore expected that additional considerations are made for the beyond design basis performance of the bearings. There is no requirement in BS EN 15129 [25] to test the bearings to failure, but this is not unreasonable given it is not intended for nuclear facilities.

It is understood that the design of the precedent nuclear facilities in France did not explicitly consider a BDB shaking but that additional load combinations have been developed by some vendors; the details of these could not be disclosed.

It is expected that the performance of the bearings under BDB shaking is justified with sufficient reliability and demonstrated through testing. It is acknowledged that quantifying the margin to failure of the bearings is not practical. It would therefore be considered beneficial to use a risk-based approach to quantify the BDB shaking instead.

The performance of the NPP under a seismic hazard greater than 150% DBE is not typically considered within the Civil Engineering design but will be relevant for the fault analysis which considers the core damage frequency and large early release frequency under fault sequences. The fault analysis may involve Probabilistic Safety Analysis (PSA) and Severe Accident Analysis (SAA) to identify initiating faults and potential consequences in accordance with SAP FA.1, FA.2 and FA.3. While it is possible to demonstrate the absence of cliff-edge effects at 150% DBE for isolated NPPs, bearing failure or the impact with a stop are likely to introduce cliff-edge effects under more extreme loading. Both situations represent a challenge for the PSA and SAA as the effects are difficult to analyse. The implications for fault analysis are beyond the scope of the research and it is recommended that they are considered further by ONR.

Expectations:	
3.5-1	The absence of cliff-edge effects in the performance of the bearings under BDB shaking should be considered and justified through testing.
3.5-2	The consequence of bearing failure or impact with the stop should be considered in the PSA and SAA.

3.6 Hazards other than earthquakes

The design of the SIS will ordinarily be governed by the seismic hazard but the performance under internal and external hazards other than earthquakes must also be considered. The following section discusses issues that were identified during the writing of this report but a detailed review of the hazards has not been undertaken.

3.6.1 Radiation

The behaviour of elastomeric bearings for exposure to levels of radiation higher than ambient is unknown as studies, either theoretical or practical, have not been carried out [38]. It is understood that current standards assume a reinforced concrete basemat will provide effective shielding from gamma and neutron radiation but some AMR designs may place bearings closer to the reactor vessel causing them to be exposed to prolonged gamma radiation. Research into the effect of gamma radiation for different types of seismic bearings are currently underway [40].

Experience from French practice is provided in Annex IV of TECDOC-1905 [7] and explains that resistance to radiation is one of the reasons for choosing the polychloroprene (CR) formulation of synthetic rubber in the elastomeric bearings. However, it also notes that the basemat provides a thick shield protecting the bearings from exposure to radiation, see Figure 1.

Alternatively, cladding the bearings in perimeter radiation-hardened protective material similar to other environmental protections may be applicable should it be deemed necessary to provide explicit protection to the bearings [38].

The potential radiation exposure of the bearings should be explicitly addressed in the safety case. It is expected that a reinforced concrete basemat would provide effective shielding but additional research is required should the design involve prolonged exposure to gamma radiation.

3.6.2 Fire

The impact of fire on the SIS must be considered as the load-bearing capacity of elastomeric bearings will degrade at elevated temperatures [39]. The US standards require the bearings to be installed in a space with a fire suppression system and free of combustible material. BS EN 1337-9 [19] Annex A recommends that bearings installed in a building with a specified fire resistance should be qualified for the same level of fire resistance as the building. In these circumstances the bearings will be required to undergo a relevant fire test with any applied protective measures in place.

It is understood that neither fire protection nor active fire suppression measures have been used on existing NPPs to protect the isolation layer. Alternative justifications have been made such as restricting fuel and ignition sources within the isolation layer and protecting the moat from external sources of fire. In addition, Annex IV of TECDOC-1905 [7] explains that the fire resistance capacity is another reason for choosing CR rubber for the precedent nuclear facilities which is understood to be self-extinguishing.

During bearing replacement and other maintenance, potential sources of fire will be introduced to the isolation layer. It is therefore expected that additional measures are considered in the replacement and maintenance plan to protect the isolation layer from fire. It is noted that the use of fire protection may increase the difficulty of inspection and maintenance of the bearings.

Limited guidance is available on the fire design of elastomeric bearings so a holistic approach to protecting the bearings from fire should be adopted. It is expected that passive methods of fire protection should be used and active measures should be considered by the RP.

3.6.3 Flooding

The effect of flooding on the performance of bearings has not been well explored so it is recommended that contact with standing water is avoided [38]. It is not expected that the bearings would need to be replaced after a short-term exposure but inspections should be undertaken. This aligns with Nuvia's experience who do not expect water to directly affect the performance of the bearings unless they are left in standing water.

It is standard practice in the US to place the SIS within a conditioned space and detail a moat cap to prevent water ingress. This is not understood to be standard practice elsewhere but would address the risk of flooding damage to the bearings and pedestals.

It is expected that the design of the isolation layer considers flooding and incorporates protective measures to prevent the bearings being in contact with standing water both during construction and operation. This may include the provision of a moat cap or active drainage systems within the isolation layer. The requirements for a moat cap are discussed further in Section 4.6.5.

3.6.4 Aircraft impact

Aircraft impact requires the assessment of the dynamic behaviour of the building and the flexibility of the isolation layer will affect the response. However, few studies have been undertaken to analyse the effect of aircraft impact on an SIS [43]. It is noted that the dynamic effects for aircraft impact may involve higher loading rates than those for seismic excitation so different mechanical properties and energy absorption of the bearings may need to be considered. However, the rate effects may not be significant if the impact is away from the isolation layer. The potential for torsional effects due to eccentric loading of the aircraft may be more significant for isolated buildings. Research in the US has shown that the displacement demands on bearings under aircraft impact loading are significant and may be larger than the DBE displacement [43]. The relative performance in the UK context has not been assessed but may be significant for the design of the bearings.

Aircraft impact may introduce other hazards to the SIS such as debris and burning fuel. The introduction of a moat cap has therefore been proposed to protect the bearings on some R&D projects as discussed further in Section 4.6.5. This follows the same principle as details on previous designs which prevent fuel entering movement joints between buildings on the nuclear island.

3.6.5 Extreme environmental conditions

The mechanical properties of the bearings are generally calculated and tested at ambient pressure, humidity and temperature at sea level. The effect of long-term elevated pressure, temperature or humidity have not been quantified and may require modifications to the testing regime and development of new rubber formulations [38]. UK conditions are generally not particularly extreme and onerous requirements are not expected to be relevant for applications within the UK context, but existing research and substantiation may not cover the full envelope of UK conditions.

BS EN 1337-9 [19] addresses protection from environmental conditions including corrosion protection. When bearings are likely to be subjected to exceptional environmental conditions then it recommends additional precautions should be taken.

Expectations:	
3.6-1	It is expected that hazards, other than earthquakes, are considered for the reliability and safety of the SIS and included in the potential failure modes.

3.7 Design life

SAP EAD.1 [1] requires that the safe working life of all SSCs are evaluated and defined at the design stage. SAP EAD.2 [1] also requires that adequate margins should exist throughout the life of a facility to allow for the effects of material ageing and degradation. The mechanical properties of elastomeric bearings may change over time if curing is incomplete, as discussed further in Section 4.3.1.4. It is therefore important that the design life of the SIS is stated in the safety case and used to evaluate the design properties and testing regime. Consideration of the construction period and decommissioning is expected to ensure the properties are valid during the operating life of the power station.

SAP EAD.3 [1] requires periodic measurement of material properties that could change with time and affect safety. The requirements for in-service testing are therefore discussed further in Section 5.3. The bearings are required to be replaceable in both European and US standards [25] [28], as discussed in Section 6.5. However, existing RGP is to design the bearings to have a working life for as long as the operational life of the NPP. A cost-benefit analysis could be undertaken to determine whether a shorter safe working life with a scheduled replacement strategy for the whole facility could be preferable.

Expectations:	
3.7-1	It is expected that the SIS is designed for the lifetime of the NPP. The RP may propose otherwise with sufficient justification and methodologies for replacement.

4. Design

4.1 Seismic analysis

4.1.1 Analysis approach

SAP EHA.6 [1] requires that the isolated facility is analysed for internal and external hazards that could affect the safety of the facility. SAP ECE.15 [1] requires that analyses to determine the structural loadings are adequately validated and verified. Therefore, the isolated facility must be analysed and designed in accordance with RGP for the seismic hazard associated with the DBE and BDB shaking as discussed in Section 3.4 and 3.5.

BS EN 1998-1 [23] does not apply to nuclear facilities but describes analysis approaches for typical isolated buildings. These include equivalent linear, modal and time history analysis with limitations on simplified methods based on the complexity of the design. The latest isolated NPPs in France used BS EN 1998-1 as the basis of the analysis with some additional criteria applied.

ASCE 4-16 [29] requires three-dimensional models using three translational components of ground motions. It allows analysis in the time domain, in the frequency domain, and the multistep method, which involves generation of the response spectra at the foundation followed by non-linear time history analysis of the isolated superstructure. It is noted that frequency domain analysis is only permitted with bearings that can be modelled accurately as linear viscoelastic elements for the chosen intensity of shaking, as discussed further in Section 4.3.1.1.

The analysis requirements in ASCE 4-16 are considered to be RGP for nuclear facilities so it is expected that the requirements in BS EN 1998-1 are enhanced accordingly. It is therefore expected that three-dimensional models using three translational components of ground motions are used for the analysis of the isolated facility.

For time domain analyses, the record-to-record variability needs to be taken into account by carrying out multiple analyses with different input ground motions. The required number of analyses depends on the required confidence level and how the results are post-processed. ASCE 4-16 requires that forces and displacements are evaluated at the 80th percent confidence level for the DBE shaking, taking into account ground motion variability and soil variability. The 80th percentile demand may be calculated directly from the observed variability of the results if using 10 or more independent ground motions. Alternatively, it can be estimated by analysing a minimum of 5 independent ground motions with each of the Upper Bound (UB), Best Estimate (BE) and Lower Bound (LB) soil properties. For any particular response quantity, the 80th percentile demand is then estimated by taking the mean result across the 5 ground motions for each set of soil properties and then taking the maximum result from the 3 sets. These are the same procedures for non-isolated facilities and were deemed to apply to isolated facilities because the dispersion in bearing properties is considered to be far smaller than those in ground motion, soil and structure [29]. This may only be true when the mechanical properties of the bearings vary less than ±20% over the lifespan of the facilities, as required in ASCE 4-16.

By comparison, BS EN 1998-1 requires a minimum of 3 ground motions. For any response quantity, the mean demand may be used if at least 7 ground motions are analysed; otherwise, the maximum result across the analyses must be considered.

It is understood that the maximum demand from 3 ground motions has typically been used on the precedent nuclear facilities. While this meets the minimum requirements in BS EN 1998-1 this is not guaranteed to meet the 80th percentile demand required in ASCE 4-16. It is considered RGP to use more than 3 ground motions to obtain a higher level of confidence in the results so the minimum requirements in ASCE 4-16 are expected to be implemented.

4.1.2 Site-independent analysis

The current approach for regulatory assessment in the UK is that a generic NPP design is assessed during the GDA and that this is checked against site-specific criteria at the site-specific design stage. A key advantage of using seismic isolation for SMRs is that the seismic demand on the superstructure can be more easily enveloped across multiple sites which minimises the amount of checking at the site-specific design stage. However, the design of the SIS itself, and structures below the isolation layer, will need to be assessed against the site-specific seismic hazard and soil conditions.

This issue is addressed by Kammerer et al. [38] who propose modifications to the certified design process in the US regulatory regime for isolated NPPs. Their proposal is that the site-independent certified design should only apply above the isolation layer, as shown in Figure 4. This approach would allow the design of the superstructure to be prequalified against a Site-Independent Certified Design Response Spectrum (SICDRS) that should include the geomean horizontal spectra and vertical spectra. At the site-specific stage, the design of the foundation and SIS would be designed for the Foundation Input Response Spectrum (FIRS) considering both the site-specific soil profile and Soil-Structure Interaction (SSI). A comparison would then be made between the seismic demand above the SIS and the prequalified SICDRS.

It is noted that while conventional isolation systems are effective at reducing the horizontal seismic demand on the superstructure, the vertical seismic demand will be site dependent. It is therefore expected that this is considered as part of the seismic design criteria for a generic superstructure.

The distinction between generic and site-specific seismic design criteria for SSCs above and below the isolation layer is important and should be clarified in the seismic design methodology.

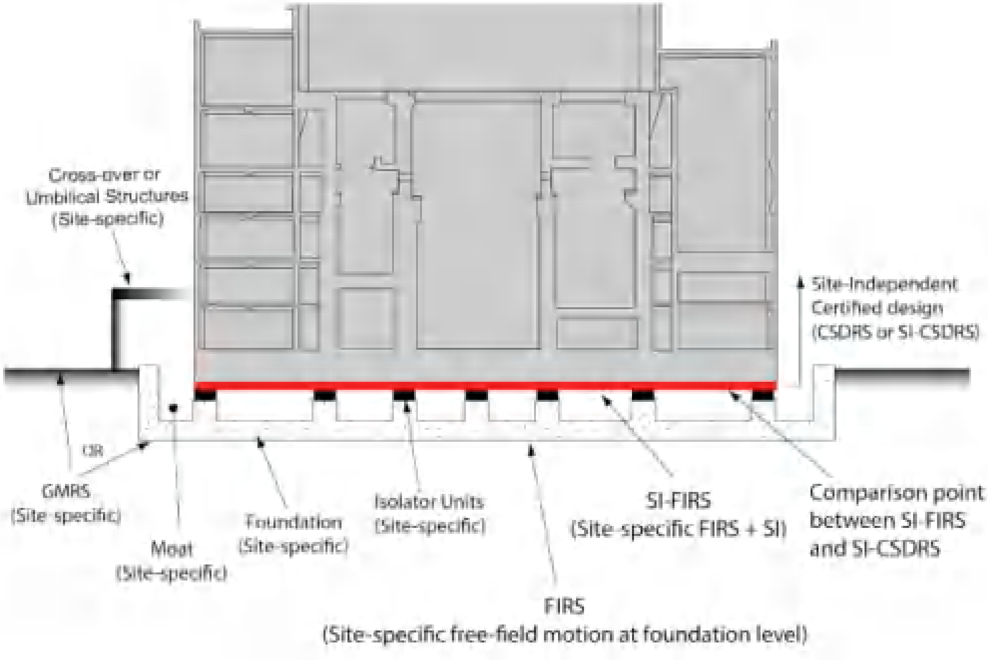

Figure 4 Definitions for evaluation of site against certified design for surface-founded, base-isolated nuclear power plant [38]

4.1.3 Structural modelling

SAP ECE.12 [1] requires that structural analysis is undertaken to support the design and demonstrate that the structure can fulfil its safety functional requirements. It is expected that the structural analyses will be undertaken with sufficient detail to determine the demands on the superstructure, bearings and substructure for both horizontal and vertical seismic excitations. The modelling approach should consider the layout of the structure and, if coupling exists, between structural responses.

The bearings should be explicitly modelled, in a spatial arrangement consistent with the final proposed arrangement. It is expected that the analyses will accurately model translation in both horizontal and vertical directions, torsion and rocking of the structure.

The bearings should be modelled as linear or non-linear elements depending on their material behaviour and should take account of the results obtained from relevant testing, see Section 4.3.1.1 for further discussion. (It is noted that the bearings used on previous NPPs are synthetic LDRBs and were modelled as linear elements.)

Rocking can lead to overturning and uplift forces on individual bearings as the net seismic force is applied above the top of the bearings. Particular attention to this effect should be considered where the bearings are less axially stiff and, in particular, when vertical isolation is included [7]. A hydraulic anti-rocking system could be employed but these require complex mechanical and digital solutions that are outside current OPEX. These systems are not considered passive and would require further research and justification.

An example of an analysis model used for a previous isolated nuclear structure is shown in Figure 5.

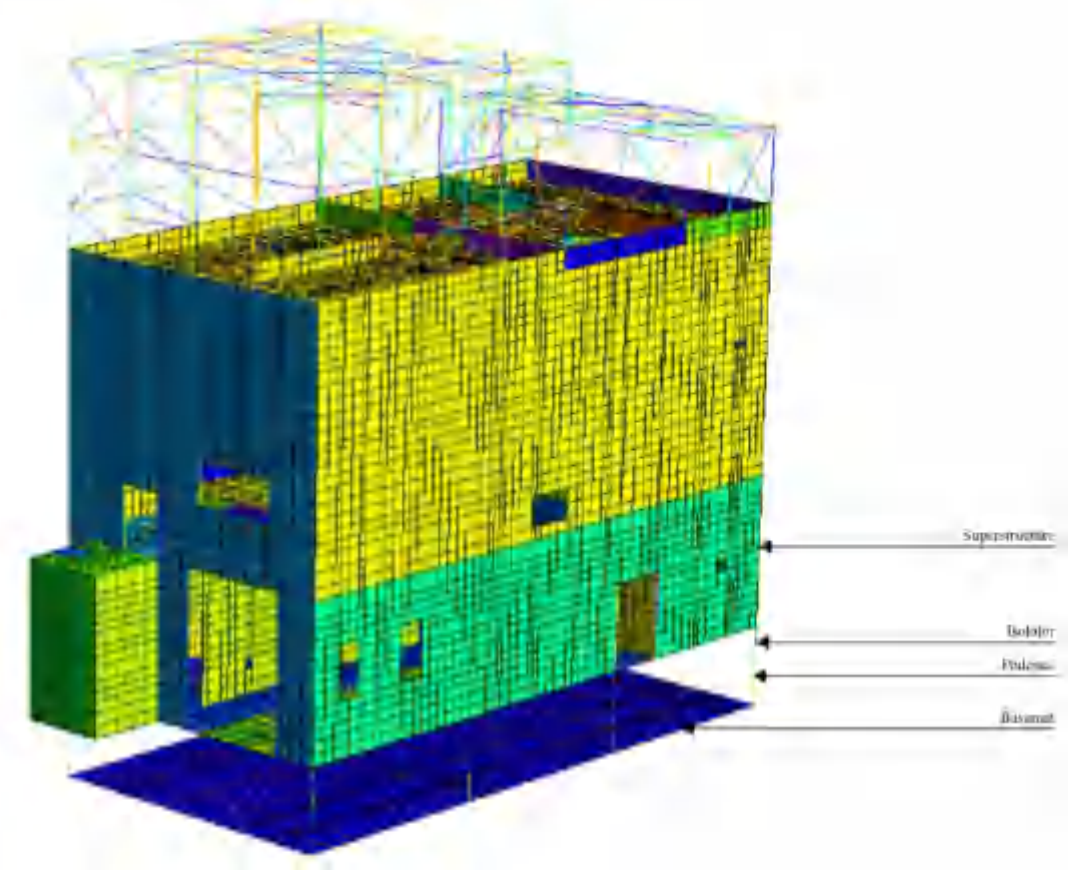

Figure 5 Example of an analysis model of isolated structure demonstrating current practice (provided by Nuvia)

4.1.4 Bearing properties

SAP ECE.13 [1] requires that data used in the structural analysis should be applied so that the analysis is demonstrably conservative. The mechanical properties of bearings can vary significantly and will affect the demands and displacements applied to the supported SSCs. It is expected that justification will be provided that the bearing properties used in the static and dynamic analysis are conservative and capture the various mechanisms discussed in Section 4.3. It is noted that there is limited guidance on the interpretation of the bearing test results for incorporation in the analysis and this should be a priority for future assessment.

SAP ECE.14 requires that sensitivity studies are undertaken to determine how sensitive the results are to the assumptions made. ASCE 4-16 [29] only requires consideration of the best-estimate bearing properties but this is only considered to be appropriate if the bearing variability is limited to ±20% over the lifetime of the NPP so is smaller than the variability in ground motion, soil and structure. If the bearing variability is greater than ±20%, it is anticipated that the seismic analysis will be undertaken for both upper and lower bound bearing properties to determine the worst case design loads. The upper and lower bound properties should be based on material data and type testing and determining these properties is discussed further in Section 4.3.2.2.

4.1.5 Soil-structure interaction

Undertaking SSI analysis, per the requirements of ASCE 4-16 [29], is considered to be RGP for the design and analysis of NPPs, including isolated NPPs. The dynamic behaviour of non-isolated structures can be highly dependent on the soil properties so warrant this level of analysis. However, it has been proposed that the seismic response of surface, or near-surface, mounted isolated structures are less sensitive to the soil profile assumptions which may allow for the reduction in the requirements for SSI analysis [38]. It is understood that the requirement for SSI analysis will be removed for surface mounted isolated NPPs in the upcoming topical report for NRC.

As noted above, the RP may claim that explicit SSI analyses are not required for verifying the design of an isolated superstructure. This is expected to be justified with sensitivity analyses that consider the range of soil properties across potential sites. While SSI effects may be less significant for the superstructure, it is expected that SSI analysis will be required for the design of the SIS, foundation and moat walls to accurately assess the seismic demand on the structures below the isolation layer.

4.1.6 Deep embedment

Seismic isolation is typically applied to surface-mounted superstructures and this is the case for the precedent isolated nuclear facilities and the basis of the requirements in ASCE 43-19 [28]. As discussed in Section 2.3, some AMRs include deep embedment such as the HTTR in Japan shown in Figure 3. It remains unclear whether such designs would employ seismic isolation for the whole facility or just at the component level [38].

For a deeply embedded isolated design, the RP may need to consider the following effects on the bearings and SIS design:

- The bearings could be installed at the upper or lower level, utilising either bottom support or hanging the structure.
- A higher aspect ratio for structures supported at the base of a deep excavation, leading to an increase in overturning and higher tension forces on bearings.
- Interaction of bearings installed at different levels (ground and base of excavation) when considering interaction between vertical and horizontal shaking.
- It may be possible to position the bearings closer to the level of the centre of mass to minimise overturning effects caused by the rigid body seismic mode which would not be possible in traditional surface mounted facilities.

The substructure design will be more heavily influenced by SSI and there are aspects of deeply embedded structures that present particular challenges [38]:

- Geometric nonlinear behaviour such as separation and sliding between the soil and structure.
- Nonlinear dynamic effects in the soil such as dynamic changes in hydrostatic pressure and shear strain (which changes the energy dissipation).
- Non-vertically propagating shear waves may be more important.

As discussed above, it is likely on deeply embedded reactor designs that the basemats will be located at multiple levels. The analysis approach discussed in Section 4.1.2 may need to be revised as there will not be a single SI-FIRS or SI-CSDRS that is most optimal. The bearings at different levels will have different inputs which are site-specific and depend on the local characteristics at that level. Advanced analysis to capture these effects may be considered for deeply embedded designs but these would be considered beyond current RGP on standard surface mounted NPPs.

Expectations:	
4.1-1	The analysis requirements in ASCE 4-16 are considered to be RGP. It is therefore expected that three-dimensional models using at least 5 ground motions for each of the UB, BE and LB soil properties are analysed.
4.1-2	The analysis methodology should consider the upper and lower bound properties of the bearings.
4.1-3	The modelling of bearings as linear elements should be justified based on relevant test data.
4.1-4	SSI effects should be considered for the design of the substructure. The omission of SSI effects in the design of the superstructure should be justified.

4.2 Bearing types

This report concentrates on elastomeric bearings as these are used on existing NPPs and are expected to be proposed for UK NPPs. Other types of bearing may be suitable but were beyond the scope of this research. More information on bearing types can be found in NUREG/CR-7253 [11] and NUREG/CR-7255 [12]. It is anticipated that further information will be available in the upcoming topical report on seismic isolation for NRC.

4.2.1 Elastomeric bearing materials

Elastomeric bearings can typically be formed using two different material types of elastomeric material, natural or synthetic. Rubber has a high elastic deformation capacity, very high elongation-at-break and a high compression stiffness.

Elastomeric bearings are constructed by bonding sheets of rubber to steel plates or shims. The steel plates do not affect the horizontal stiffness of the bearing but substantially increase the vertical stiffness of the bearing and prevent it from bulging under vertical loads.

The rubber properties can be modified during vulcanisation (curing) by using additives such as accelerators or fillers that are discussed below. The mechanical properties associated with different rubber formulations are defined in BS EN 1337-3 [18] with references to the testing requirements to verify these.

4.2.1.1 Natural rubber

Natural rubber (NR) is the preferred low damping base material in the US. Natural rubber is derived from latex and becomes the chemical "isoprene" if purified. NR has been widely used in the US for critical applications and has a proven track record. The mechanical properties are also not expected to change over the lifetime of the nuclear facility which is preferable to other rubber formulations [11].

No NPPs have been isolated in the US to date and the use of NR has not been implemented in this context.

4.2.1.2 Synthetic rubber

Synthetic, or artificial rubbers, such as neoprene are manufactured by introducing additives or fillers during the vulcanisation process. This modifies the rubber properties including the rubber strength, elasticity, sensitivity to temperature, resistance to solvents, stiffness, hardness, creep, elongation-at-break and fatigue life [11].

Synthetic rubber is currently not permitted for use on nuclear facilities in the US as the mechanical properties vary from compound to compound and typically have undesirable properties such as scragging (change in material properties, typically associated with the first few cycles of loading) and ageing, which change the mechanical properties through the life of the nuclear facility [11]. While the use of synthetic rubber increases the variability of bearing properties, it is considered feasible to determine the variability and incorporate this into the analysis.

The formulation used on the French NPPs is polychloroprene (CR). The changes in properties associated with scragging and ageing are accounted for in the design of the isolation system and are checked that they are within the design envelope.

CR is less stable at low temperatures and has a higher glass transition value. Therefore, this formulation is typically not used on bridges or exposed bearings where temperatures can drop to low values. The area below a NPP is more stable and if low temperatures are expected, these can be locally protected.

4.2.2 Elastomeric bearing types

4.2.2.1 Low damping rubber bearings

LDRBs are elastomeric bearings and can be formed of either natural or synthetic rubber. LDRBs are classified in BS EN 15129 [25] as elastomeric bearings with an effective damping ratio of less than 6%. LDRBs are therefore most commonly used in low-seismic regions or in parallel with additional damping devices.

LDRBs using CR have been used in the precedent NPPs and nuclear facilities in France and South Africa.

4.2.2.2 High damping rubber bearings

HDRBs are elastomeric bearings which are formed of synthetic rubber such that the natural mechanical characteristics of rubber including the hardness, stiffness, damping, elongation-at-break, creep and relaxation properties can be modified. HDRBs are classified to have a damping ratios greater than 7% of critical with some formulations having up to 13%.

HDRBs are known to have been used for equipment isolation and on auxiliary buildings within NPPs but not for SSCs on the nuclear island.

4.2.2.3 Lead rubber bearings

Lead rubber bearings (LRBs) are formed by inserting a lead core into the centre of an LDRB. This increases the damping ratio of the bearing through the plastic deformation of the lead core. The lead core is stiff below yield and then close to perfectly plastic above yield. Lead also has the ability to recover its initial mechanical properties after deformation, and is cold-worked at room temperature, leading to favourable low-cycle fatigue properties.

LRBs have not been used on reactor buildings but have been used for an emergency response building at the Fukushima NPP in Japan [11]. LRBs are common for building, bridge and infrastructure isolation and have been used in the US on the San Francisco City Hall, the Golden Gate Bridge and University of Southern California University Hospital. It is expected that LRBs would be used for NPPs in the US where higher damping ratios are required.

4.2.3 Complementary devices

4.2.3.1 Flat surface sliders

Flat surface sliders (FSSs) have been used in an NPP precedent, Koeberg, in South Africa. Koeberg utilised FSSs in series with LDRBs to limit the lateral force transmission through the bearing to the frictional resistance of the sliding interface. This type of sliding device has no recentring ability so therefore would not meet the current requirements in BS EN 15129 or ASCE 43-19 [28] as a primary device or in series with a primary device, as used at Koeberg.

FSSs are sometimes used in parallel with other devices which have sufficient recentring capability, to provide additional loadbearing capacity with minimal impact on the horizontal stiffness. The introduction of FSSs can allow the vertical load to be distributed more evenly across the basemat and tune the vertical load in the elastomeric bearings. This may allow the horizontal isolation stiffness to be more efficiently designed for a target fundamental period. However, elastomeric bearings shorten under horizontal deformation whereas FSSs do not which makes it difficult to predict the distribution of vertical load under seismic actions. This is undesirable and must be justified if the devices are used in parallel.

ASCE 43-19 prohibits the use of hybrid isolation systems involving different types of bearings.

It is not expected that FSSs will be proposed in the UK as either a primary or secondary device.

4.2.3.2 *Viscous dampers*

Viscous dampers are often used in parallel with LDRBs, LRBs and CSSs to increase the damping of the SIS. The dampers do not provide any additional stiffness to the system and do not carry vertical load, unlike an FSS. Damping is used to reduce the displacements of the SIS and demands for the supported SSCs.

Viscous dampers have not been used as part of the SIS on previous NPPs, although they are commonly applied in non-nuclear applications in areas of higher seismic hazard. An example cross-section is shown in Figure 6. However, viscous dampers have previously been used as shock restraints on safety related pipelines suggesting that they can achieve the increased level of reliability required in nuclear applications.

Viscous dampers are addressed in BS EN 15129 [25] Section 7 requiring a series of Type and FPC tests to be undertaken. Enhancements to the requirements of Section 7 for viscous dampers in the nuclear context has not been investigated in this report.

Due to the level of seismic hazard in the UK, it may not be necessary for the proposed SIS to include supplementary damping to control the displacements.

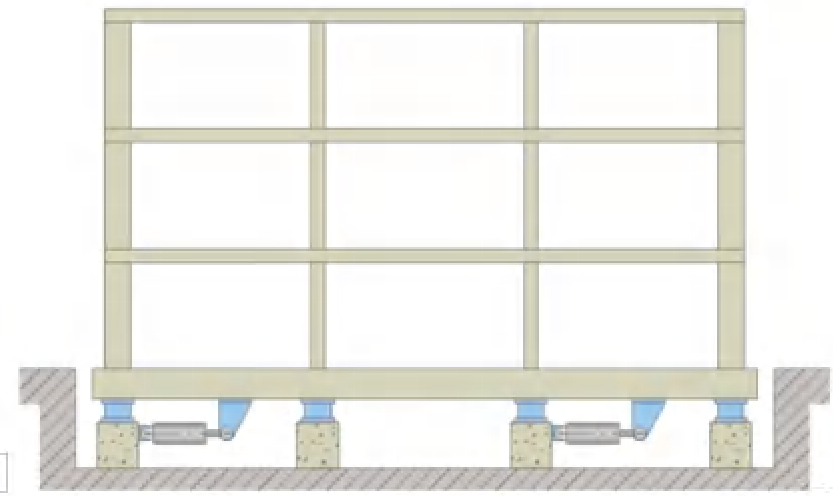

Figure 6 Cross-section of an isolation design with supplementary viscous dampers (provided by Nuvia)

4.2.4 Precedent nuclear facility bearings

Refer to Table 1 for information regarding the bearing sizes and specifications from Nuvia's experience on the precedent NPPs and other nuclear facilities such as R&D reactors, uranium conversion and enrichment facilities, and nuclear fuel recycling facilities. It is noted that all of the bearings used to isolate a reactor to date have been LDRBs made with synthetic rubber.

Expectations:	
4.2-1	The suitability of synthetic rubbers and HDRBs should be demonstrated in the safety case considering potential changes in mechanical properties throughout the life of the NPP.

Table 1 Bearing types used on existing nuclear facilities (provided by Nuvia)

Project	Owner	Type of isolator system	
		Isolator Type	**Number**
ITER (France)	Fusion for Energy – ITER	Isolators (CR): Elastomeric bearings Dimension: 900 x 900 x 181 mm	493 bearings
RJH (France)	GME RAZEL - BEC	Isolators (CR): Elastomeric bearings Dimension: 900 x 900 x 181 mm	195 bearings
EDF Cruas (France)	EDF CNPE Cruas	Isolators (CR): Elastomeric bearings Dimension: 500 x 500 x 66.5 mm	3600 bearings over 4 units on the nuclear power plant REP 4 x 900 Mwe
AREVA La Hague (France)	AREVA La Hague	Isolators (CR): Elastomeric bearing Dimension: 700 x 700 x 147 mm 10 layers x 10 mm rubber 9 x 3 mm thick steel plates + 2 external 10 mm-thick steel plates	182 doubles bearings (58 C, 60 D, 64 E)
ESKOM Koeberg South Africa	ESKOM Koeberg	Isolators (CR): Elastomeric bearing Dimensions: 700 x 700 x 130 mm coupled with friction flat sliders (lead bronze plates)	1800 bearings
ORANO La Hague (France)	ORANO RECYCLAGE	Isolators (NR): HDRB S Ø250 x 50 mm 9 internal steel plates 2 mm thick, elastomeric rubber layers 5 mm thick, external belt protection 5 mm thick.	24 bearings
ORANO Tricastin (France)	ORANO RECYCLAGE	Isolators (CR): Elastomeric bearings Dimension: Ø500 x 334 mm 21 internal steel plates 22 elastomeric rubber 13.3 mm thick	1680 bearings
U5 Filter (Blayais, Dampierre, Gravelines, Tricastin, Chinon, Saint Laurent, Flamanville, Paluel, Saint Alban)	EDF	Isolators (CR): Elastomeric bearing dimension: 242 x 242 x 140 mm 10 layers x 8 mm rubber 9 x 2 mm thick steel plates + 2 external 20 mm-thick steel plates	6 bearings per site
ITER (France)	ITER ORGANISATION	Isolator support for cryostat Spherical mechanical bearings Ø900 x 750 mm	18 bearings + 2 spares

4.3 Bearing mechanical properties

The mechanical properties of the bearings are highly dependent on the rubber formulation and the vulcanisation process used during the manufacturing process. Therefore, quality control and verifying properties from testing for rubber materials are required by the standards for both nuclear and non-nuclear applications. The variation in characteristics is verified by testing, typically on full-scale prototypes, and is discussed in more detail in Section 5.1.

4.3.1 Material properties

4.3.1.1 Shear

Properties of bearings in shear are the most critical for the design of seismic isolation, and they vary significantly amongst the different bearing types. The shear behaviour is typically described using the shear strain which is defined as the ratio of shear deformation to the total thickness of rubber.

LDRBs typically exhibit linear elastic behaviour up to 200% shear strain and stiffen above this level [11]. The bearings can therefore be modelled as linear elastic elements when undergoing analysis up to approximately 200% shear strain. Under higher strain levels, non-linear models of bearings should be used and time domain analysis undertaken, as discussed in Section 4.1.1. The shear modulus, G, can vary typically between 0.45 MPa and 0.7 MPa at 100% shear strain.

The shear stiffness of a HDRB is non-linear. The initial stiffness of the bearing is relatively high, helping to control wind-induced displacements. At moderate shear strains, the stiffness decreases. At larger strains, the horizontal stiffness increases again helping limit the maximum horizontal displacements. The maximum shear strain of failure ranges typically from 200% to 350% depending on the formulation of the rubber [11]. The shear modulus, G, can range from 0.35 MPa to 1.40 MPa.

The shear stiffness of LRBs is controlled by the stiffness of the lead core within its elastic range, and by the stiffness of the rubber when the lead core yields. The characteristic strength in shear of an LRB is governed by the dynamic yield strength, size and instantaneous temperature of the lead and the degree of confinement of the lead core. The post yield stiffness is a function of the shear modulus of the rubber, the total bonded area and the total thickness of the bearing. Typically, the maximum shear strain ranges from 125% to 200% [11].

Typically, the maximum shear strain at first damage of bearings ranges from 300% for stiff bearings (shear modulus greater than 1.1 MPa) up to 350–400% for soft bearings (shear modulus less than 1.1 MPa) [6].

4.3.1.2 Compression

The vertical stiffness and buckling capacity of an elastomeric bearing are dependent on its geometry. A shape factor is used to quantify these effects which is defined as the ratio of the bonded diameter to four times the thickness of a single rubber layer. The shape factor for seismic bearings is typically greater than 10 and sometimes greater than 30. High shape factors help to minimise shear stress caused by compressive loads and increase the buckling capacity of the bearings [11].

LDRBs exhibit high vertical stiffness when subjected to compressive loading due to the incompressibility of the rubber combined with the confining effect of the steel shims within the rubber matrix that prevent bulging.

The addition of fillers, additives or a lead core does not significantly affect the vertical stiffness and therefore HDRBs and LRBs have similar compressive properties to LDRBs [11].

The axial force on the bearings can affect the shear stiffness, causing the bearings to become less stiff horizontally as vertical load increases [45]. The effect is most pronounced on bearings with small shape factors and can become a limiting factor as the bearings approach their buckling load.

Buckling failure load in compression also varies with lateral displacement, decreasing as lateral displacement increases. The critical load can be calculated from an area reduction method, which predicts that a bearing will have no vertical capacity at a horizontal displacement equal to the width or diameter of the bearing. In reality, the bearings maintain a degree of capacity at this displacement, so this method is conservative.

For small shape factor bearings, this effect couples the horizontal and vertical responses which should be captured in the analyses.

4.3.1.3 Tension

For small tensile forces the axial stiffness is similar to the stiffness in compression. For larger tensile forces the bearing will develop cracks in the volume of the rubber, an effect called cavitation. Typically, cavitation occurs at tensile stresses equal to approximately 3G, where G is the shear modulus of the rubber. This corresponds to tension between 1.5 MPa and 2.5 MPa. This effect is consistent amongst the different elastomeric bearing types.

Once cavitation occurs, confinement due to the steel plates is lost, and the tensile stiffness decreases by several orders of magnitude. The substantial loss in stiffness will effectively allow uplift of the bearings and only high-quality construction can sustain the rubber extension without rupture. Experiments undertaken at University of Buffalo showed that cavitation did not cause a significant change in the shear stiffness, compressive stiffness and buckling load [12].

4.3.1.4 Ageing

Rubber is a material which changes as it ages. The shear stiffness of both natural and synthetic rubber increases over time. The ageing process is due to the fact that the vulcanisation (curing) process is not fully complete at the time of bearing manufacture and installation, and it continues over the life of the bearing. If the curing process is allowed to fully complete then the age-related effects will be minor.

Properties can also degrade due to exposure with oxygen and ozone which typically affects a thin outer layer of the bearing. Often the bearings are fabricated with a cover layer on their exposed surfaces with antioxidants and antiozonants to protect the core of the bearing [35].

The change in properties with age is a critical aspect of the qualification process and should be accounted for in the upper and lower bound properties of the bearings.

4.3.1.5 Temperature variation

The mechanical properties of rubber, including both the shear stiffness and damping, are dependent on temperature. The effect with temperature is non-linear and the properties are more sensitive to temperatures below ambient than high temperatures, as shown in Figure 11. Below the glass transition temperature rubber becomes brittle and both the mechanical and physical properties undergo significant and rapid changes. The duration of exposure to cold temperatures can also influence both the stiffness and the damping of the bearing.

Synthetic rubber, CR, is affected to a greater degree by cold temperatures than NR so is typically not permitted for use on bridges and other external environments. The isolation layer of a building may be open to the external environment but the temperature variation is typically less than a fully exposed condition. The conditions on the precedent nuclear facilities in France were demonstrated to be suitable for the use of CR [11].

The US practice is to install bearings in an air-conditioned space that controls the temperature variation of the bearings. This is considered to be beneficial particularly if there is a risk of low temperatures within the isolation layer.

The effect of temperature is addressed specifically in the qualification process and should be accounted for in upper and lower bound properties of the bearings.

4.3.1.6 Creep

Creep is an effect which leads to the shortening of a bearing subjected to compression loads over time. This can cause redistribution of vertical load through the isolation layer and may lead to changes in horizontal stiffness of adjacent bearings. The effect of creep should be predicted in the analysis and monitored throughout the life of the NPP.

4.3.1.7 Scragging

Scragging is a reduction in the horizontal strength and stiffness of a bearing under multiple cycles of loading. The original properties are called virgin or unscragged properties. The effect of scragging usually decreases the stiffness to a stable but lower value than the virgin properties. It is sometimes assumed that the changes of stiffness produced by scragging are permanent, however there is generally a significant recovery of the virgin properties over time [25].

Scragging is considered to have a negligible effect on LDRBs fabricated with natural rubber when the shear modulus is greater than 0.45 MPa.

Scragging affects HDRBs more significantly, leading to a reduction in the horizontal stiffness and strength under repeated loading cycles. The effect increases as the volume fraction of fillers increase and is considered a major issue that prohibits the use of HDRBs in the US. The guidance in NUREG/CR-7253 [11] allows only minor changes in the isolator properties due to scragging which limits the materials that can be used in US NPPs.

4.3.1.8 Loading rate

The effect of loading rate is not considered significant on the mechanical properties of LDRBs. HDRBs are moderately affected as the horizontal stiffness and damping increase as the loading rate increases.

The effect of the loading rate on LRBs is dependent on the strength and energy dissipated by the lead plug. As the cycles increase the energy dissipated reduces as the temperature of the lead core increases due to the plastic deformation.

4.3.2 Discussion

The variability in the mechanical properties of isolation bearings is important to capture due to its influence on the effectiveness of isolation. The bounding of properties to enable realistic upper and lower bound scenarios allow the designer to capture the uncertainty in the bearing material through enveloping within the analyses. It is important to consider how the upper and lower bounds are calculated and that multiple variables are combined to produce a conservative but efficient design.

4.3.2.1 Allowable variability

ASCE 4-16 [29] prohibits the use of bearings which have material properties that vary by greater than 20% from the design and analysis values (cl. 12.2.2.1) for the lifespan of the nuclear structure. Variations should account for the isolator properties at construction, ageing, operating temperature and creep. There is an exception to this clause which allows greater variability if the BDBE performance at the 90th percentile is evaluated explicitly rather than scaling the DBE mean displacements, as discussed in Section 3.5. Restricting the variability of the bearings to less than ±20% avoids the need to bound the properties in the analysis, as discussed in Section 4.1.1. This is considered an acceptable approach but has not been followed on the precedent nuclear facilities.

HDRBs and synthetic rubber bearings are considered inappropriate for use in the US [11] due the variation in mechanical properties caused by scragging and ageing. The report suggests that with improvements and standardisation then there may be routes for the use of HDRBs and synthetic rubbers in the future on NPPs in the US.

It is accepted in BS EN 15129 [25] that the variability of the bearing properties may be greater than 20%, with variations of up to 80% permitted for temperature variation alone. This is discussed in more detail in Section 5.1. In addition to this variability, an allowance of 20% for variation between factory control testing and type testing, as discussed in Section 4.3.2.2, is accepted.

The upper and lower bound properties are determined and accounted for explicitly in the design using the EN approach and is addressed in Section 4.3.2.2.

ASCE 7-22 [30], the US non-nuclear standard, allows the use of λ factors in Table C17.2-7 that may be used to scale the upper and lower bound values from mean tested characteristics. The values provided suggest that for elastomeric bearings and LRBs, lower and upper bound properties may be taken as 0.8 to 1.3 times the mean, respectively. The upper bound value would not satisfy the 20% variability limit in ASCE 43-19 [28].

ONR regulatory expectations are based on general principles, rather than explicitly defining allowable technologies. Therefore, it is expected that the use of LDRBs or HDRBs would be permitted as long as upper and lower bound properties are explicitly accounted for in the design.

4.3.2.2 Combining properties to determine upper and lower bounds

BS EN 15129 [25] states that test results should be adjusted by an ageing factor, temperature factor and the Factory Production Control (FPC) test tolerance of ±20% to calculate the Lower Bound Design Properties (LBDP) and Upper Bound Design Properties (UBDP). These have been combined in previous precedent designs using the equations below.

$$LBDP = K_{eff,nom} \times (1 - [FPC\ test\ tolerance])$$

$$UBDP = K_{eff,nom} \times [ageing\ factor] \times [temperature\ factor] \times (1 + [FPC\ test\ tolerance])$$

The factors are material specific and are calculated based on the testing regime of the product. If the variability in the vulcanisation process and scragging are within the acceptance criteria of the type testing to BS EN 15129, referenced in Table 2, then this is captured in the FPC test tolerance rather than explicitly accounted for.

It is expected that a more rigorous understanding of the material properties will be required for NPPs and therefore it is expected that the additional effects detailed above, including the effect of scragging, creep, and variability in base material, should be explicitly accounted for in the definition of the LBDP and UBDP. This is especially important for high-damping rubber bearings which can undergo significant scragging during operation. The above equations do not provide a confidence level or risk associated with the UBDP and LBDP.

BS EN 1990 [22] Annex D demonstrates a methodology for determining characteristic values of materials based on test results, achieving the 95^{th} and 5^{th} percentile values for UBDP and LBDP respectively. This methodology is not known to have been adopted for determining the characteristic material values for bearings. In any case, it is expected that the variations described above are included in the determination of the UBDP and LBDP properties to achieve a quantifiable level of reliability.

It is noted that the approach for defining the lower and upper bound properties is based on the expected variability of individual bearings rather than considering the variability over the SIS as a whole. The variability over the whole system will be less but there is no guidance on how to quantify this. It is noted that many causes of the variability will be correlated such as temperature and ageing so the benefit may also be limited.

Expectations:	
4.3-1	It is expected that the range of bearing properties used in design are determined through testing and their sensitivity to the analysis is determined.
4.3-2	It is expected that the results of the tests are combined to provide upper and lower bound properties to envelope the NPPs seismic performance using a statistical methodology such as that described in BS EN 1990 Annex D.
4.3-3	If the effects of scragging are significant these should be explicitly accounted for in the upper and lower bound properties.
4.3-4	It is expected that the design life of the bearings will be at least the design life of the NPP so that they would not require full replacement during the initial NPP design life.

4.4 Bearing limits

The design of the bearings must consider the deformation and strength capacity as justified by testing. The limits discussed below are typical for elastomeric bearings.

4.4.1 Shear strain

It is recommended by ENEA [6] that the maximum shear strain at DBE is limited to 100% providing a typical margin of 3.0 with respect to first damage. While this low shear strain limit increases the reliability of the bearings, it is noted that this will increase the size of bearings and cause increased cost in terms of manufacturing, testing, installation, and maintenance. This limit is consistent with the limits used on the precedent nuclear facilities in Nuvia's experience.

It is expected that the reliability of the bearings at DBE should be quantified, as discussed in Section 3.4, instead of relying on a limit of 100% shear strain.

4.4.2 Compressive stress

The typical compressive stress limit for bearings is between 20 and 25 MPa with a working load of approximately 10 MPa. The vertical stress limit is sufficiently far from the ultimate capacity to ensure that buckling does not occur under horizontal displacement. Typically limiting the shape factor to be greater than 10 reduces the risk of buckling failure.

4.4.3 Tension

Tensile deformation of elastomeric bearings is considered undesirable due to the permanent damage caused by cavitation. Codes therefore typically require no tension on elastomeric bearings in seismic conditions and some require a residual compressive stress [7]. It is understood that a tensile limit of 1 MPa is employed for the design of elastomeric bearings in Japan and China.

Tension in the bearings can be avoided under DBE loading by controlling the number of bearings specified and their spatial distribution. On the precedent isolated nuclear facilities, the designs were checked for a minimum of 1 MPa in compression on each of the bearings under the DBE load case.

There are no requirements for testing under tension in either BS EN 15129 [25] or ASCE 43-19 [28] to demonstrate the tensile performance. Tensile testing is considered necessary if the bearings go into tension under DBE or BDBE ground shaking. It is therefore expected that tensile stresses in the bearings are avoided under DBE ground shaking.

4.4.4 Recentring behaviour

Both the US and European approaches require that bearings are capable of recentring following a seismic event. The approach taken however is defined differently, with BS EN 15129 defining a minimum stored internal energy of the isolator (cl. 4.5.3 (6)) while ASCE 4-16 [29] defines a minimum lateral restoring force that increases as the shear displacement increases.

The experience from the isolated nuclear facilities in France is that LDRBs specified using BS EN 15129 act in the elastic region so have an inherent recentring ability.

The existing NPP in Koeberg, South Africa, as described in Section 4.2.3.1, utilises FSSs which would not meet the recentring requirements of either ASCE 4-16 or BS EN 15129.

The requirements for recentring in BS EN 15129 and BS EN 1998-1 are for the DBE ground shaking. Permanent displacement under BDBE shaking would typically be considered acceptable for non-nuclear applications including a lack of recentring. However, this is not acceptable to ASCE 43-19 for nuclear facilities.

4.4.5 Temperature

The US practice is to install bearings in a dry air-conditioned space that fluctuates within the range of 4.4°C (40°F) and 26.7°C (80°F) [11]. The isolation layer in the operational NPPs are not conditioned but this option should be considered as a way to limit the variation of bearing properties with temperature. It is anticipated that should a non-conditioned isolation layer be proposed, the RP would be expected to justify the approach.

The approach of BS EN 15129 [25] does not specify an allowable operating temperature range but requires type testing to qualify the proposed range, as discussed in Section 5.1.7. Should predicted temperatures within the isolation layer fall outside of these limits, it would be expected that either a new material would be proposed, or localised protection would be provided to ensure that the temperature of the bearings would remain within acceptable limits.

If temperatures are reached within the bearing that are lower than the glass transition temperature, the bearing response under lateral loads may become brittle, and the ultimate displacement capacity may be reduced. During the qualification tests, it should be verified that the ambient low temperature is higher than the glass transition temperature of the bearing material.

Expectations:	
4.4-1	Tensile stresses in the bearings should be avoided under DBE ground shaking unless testing is undertaken to justify the performance under tension.
4.4-2	The temperature range within the isolation layer should be calculated and the impact on the bearing properties assessed. The use of a conditioned space should be considered to avoid temperatures outside of the range 4.4°C to 26.7°C.

4.5 Stop

As discussed in Section 3.3, a stop surrounding the SIS can be used to remove shear failure of the SIS from the failure sequence for the supported SSCs. This is considered to be beneficial due to the lack of resilience to a CCF or ductility within the SIS and the possibility of cliff-edge behaviour if displacement capacity of the bearings is exceeded.

A stop is a current requirement for seismically isolated nuclear facilities in the US, as outlined in ASCE 43-19 [28], to prevent excessive displacement of the isolation system in the event of BDBE shaking. The expected approach to meet this requirement is to provide a moat wall which the superstructure would impact should excessive displacements occur. This is not a requirement for non-nuclear isolated facilities.

It is understood that the requirement for a stop will be removed from the upcoming topical report for the NRC as they transition to a risk-based approach for the design of the isolation system. This report is yet to be published so has not been included as part of this research.

BS EN 15129 [25] prohibits the use of an end stop to be placed on FSS and CSS bearing types to avoid impact between mechanical elements causing damage to the components in the event that displacements are greater than the DBE displacement. This is not specifically required for elastomeric bearings.

A stop has not been implemented on existing NPPs in France.

4.5.1 Clearance to the stop

The distance between the isolated structure and the stop is defined in the US standards to be no less than the 90th percentile BDBE displacement. ASCE 4-16 [29] allows this to be taken as 3 times the mean displacement at DBE based on research undertaken by Huang et al. [36]. This study was undertaken for 3 sites in the US considering different bearing types including both elastomeric and friction pendulum bearings. There was a reasonable variation in the BDBE displacement but 3 times the DBE displacement was generally found to be conservative for the range of hazards, locations and bearing types.

It is noted that the 3 times DBE displacement defined in ASCE 4-16 is based on research undertaken in the US context and while this may still be conservative for the UK, it should be justified based on the design seismic hazard and bearing properties. The distance for the stop will need to be justified in the UK context depending on the BDBE definition and the reliability factors used for the bearings under the DBE.

4.5.2 Impact behaviour

The isolation bearings inherently have cliff-edge effects at the point of instability and buckling failure. The stop acts to prevent this cliff-edge effect by imposing a limit on the displacement defining a margin to failure of the system that can be determined through the testing regime. The impact on the stop must instead be considered as an accident scenario and appropriate design of the stop, the superstructure and the reactor should be considered.

The lack of design guidance for the impact with the stop has been highlighted as a weakness of the requirement but it is noted that impact would only occur at ground shaking in excess of the BDBE which would not typically be considered within the Civil Engineering design, as discussed in Section 3.5. The requirements for the design of impact should therefore be developed as part of the PSA and it is recommended that this is discussed further as a cross-discipline topic.

The US standards require the stop to be designed for impact loadings but do not provide any guidance. One approach that has been proposed is basing the velocity and acceleration of the superstructure on it displacing cyclically at the 95th percentile displacement at a frequency equal to the isolation frequency [38]. This leads to relatively low impact forces and implies that the superstructure could be designed for these forces. The torsional response of the superstructure can lead to impacts at discrete locations rather than along edges of the superstructure and therefore there may be many configurations to be considered in the design.

The US standards do not require the supported SSCs to be analysed for impact loadings provided the distance to the stop equals or exceeds the 90th percentile BDBE displacement. However, the standards do not address risks to the reactor or safety critical SSCs and the effect of impact should be considered as part of the PSA.

4.5.3 Construction details

There is a lack of analysis, design and detailing examples of stops, since they are only required in US practice, and seismic isolation has not yet been implemented on nuclear facilities in the US.

If the stop is constructed using reinforced concrete as a hard stop, it would be expected that it is constructed using ductile detailing to allow energy absorption upon impact [38]. Alternatives to a hard stop have been considered but not implemented. The material for a soft stop would need to be suitable for the exposure environment.

The recent SILER R&D project investigated the introduction of a soft stop using marine fender devices which are used to absorb energy in boat impact design cases for docking structures. The distance to the stop was approximately 3–4 times higher than the design displacement. The use of shock absorbers reduced the impact loads on the stop by an order of magnitude but did not consider the effect on supported SSCs [41]. The disadvantage of this proposal was that the displacement to the stop would need to be increased to account for the flexibility and compressibility of the soft stop.

Expectations:	
4.5-1	Where a stop has been provided, the clearance to the stop should exceed the BDBE displacement to prevent cliff-edge effects due to impact.

4.6 Foundation design

The foundation refers to all the elements of the structure that are below the isolation layer. This includes the pedestals, raft and any retaining walls. The isolation layer comprises the void space between the building basemat and the foundation isolators where the pedestals isolators are situated. Typically, the isolation layer is below the surrounding ground level so retaining walls are present on most designs. These may be large for deeper designs. Figure 7 shows the typical arrangement and naming convention for elements within an isolated building.

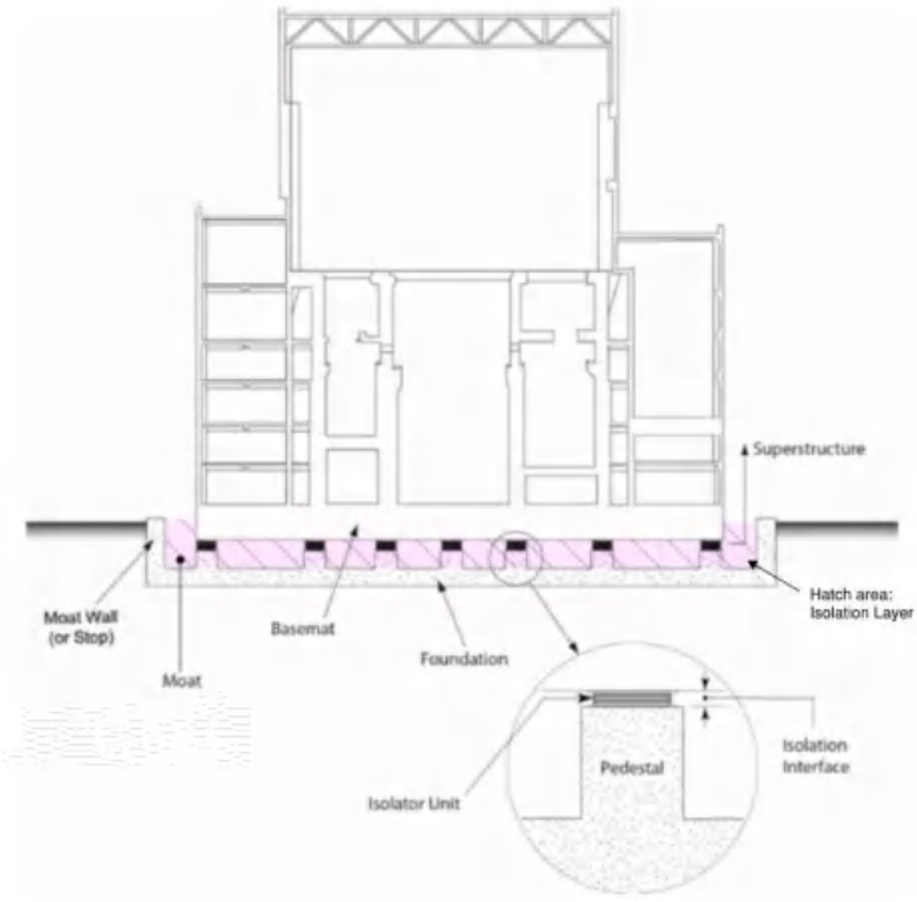

Figure 7 Seismic isolation of light water reactor [38] with additional call-outs

4.6.1 Capacity design

BS EN 15129 [25] implements capacity design for the isolator connections through an overstrength factor of 1.1 applied to the upper bound demand of the isolator at DBE [25]. This methodology is understood to have been used on the ITER project.

To avoid damage in the foundation, the US standards require the pedestal, connections and raft to be designed for the full isolator demand at the stop; i.e. when all bearings are at their maximum displacement [28]. This ensures that damage will not occur in the foundation at seismic demands less than the BDBE, as discussed in Section 3.3. Due to torsional effects in the superstructure it is likely that the bearings will not reach their peak response simultaneously. This beneficial effect should not be considered, according to the standards.

The precedent NPP in Koeberg utilised an FFS to act as a “fuse” to limit the force to the frictional interface capacity. Alternative methods to limit the transfer of force using a “fuse” could be proposed to meet the capacity design requirement at BDBE excitation but this is not considered necessary.

It is expected that capacity design is implemented for the foundation design including the pedestals, connections and raft and that the design considers the demand of the bearings at BDBE.

4.6.2 Pedestal design and connections to the bearings

The bearings are typically installed on reinforced concrete pedestals which are situated on the raft foundation. The pedestals raise the bearings up so that there is sufficient space to enable access and replacement of the bearings as well as facilitating inspection and maintenance.

The horizontal load needs to be transmitted to the structure using mechanical components and may not consider the transfer of load through friction [25]. This is typically achieved with the use of anchor bolts and/ or pins to fix the base plate of the isolator to the pedestal below and basemat above.

Nuvia's operational experience has suggested that the connections between the bearings and the pedestals are required to be mechanical rather than relying on the levelling grout beds and friction. The mechanical fixings are designed without the benefit of friction or shear interlock. TECDOC-1905 also suggests that without mechanical fixings the bearings are more sensitive to instability effects such as rollover [7].

The bearings can be fixed in a variety of ways however typical precedents show cast-in plates with shear studs and bolted connections between the isolator end plates and the cast-in plates. Further discussion on the installation is included in Section 6.1.

The pedestals should be designed without inelastic action and detailed for a ductile response. One approach to this would be to use the prescriptive rules set out in RG 1.142 [15] and ACI 349-13 [27], similar to all other concrete elements within the NPP.

4.6.3 Raft

The foundation raft is required to have enough stiffness so that all the bearings are engaged under both gravity and lateral loads [11]. Therefore, the raft must resist localised settlement and movements of the retaining walls to ensure that the distribution of loads in the bearings is maintained. As settlement may occur over the life of the NPP, a monitoring scheme is recommended to check how settlement progresses against predictions. Refer to Section 6.4 for further details of the required monitoring and inspection programme.

4.6.4 Retaining (moat) walls

The design of the retaining walls should be the same as for a non-isolated building. As the walls are typically unpropped to provide the seismic movement gap with the superstructure, then the static and seismic demand may be relatively onerous. It is important to consider both the static deflection of the wall and the seismic movements to ensure these are coordinated with any required clearance to the stop.

The design of the moat walls may also need to consider the impact from the superstructure as discussed in Section 4.5.

4.6.5 Moat cap

A seismic gap or moat must be present around the superstructure to allow for the predicted movements of the isolated superstructure. The bearings may therefore be exposed to the external environment and external hazards, such as fire, flooding and aircraft impact, as discussed in Section 3.6. A moat cap can be introduced to provide the following protection:

- Weatherproofing (prevent water ingress from rain, snow, flooding and tsunamis)
- Fireproofing (prevent burning fuel or other materials or fluids from entering the isolation layer)
- Resistance to impact (such as airplane impact)

On previous NPPs the moat has been left open but a cap has been proposed on R&D projects as shown in Figure 8 and Figure 9. The proposals in Figure 8 are intended to protect the isolation layer from airplane crash debris and prevent ingress of kerosene. The device shown in Figure 9 only satisfies movements up to DBE and does not consider BDB shaking without activation of a mechanical fuse to allow further movement.

It is standard practice in the US to place the SIS within a conditioned space and detail a moat cap to provide environmental protection. It is expected that the isolation layer will be suitably protected from external hazards which may cause damage to the SIS. The implementation of mitigation measures such as a moat cap and storm drains should be considered.

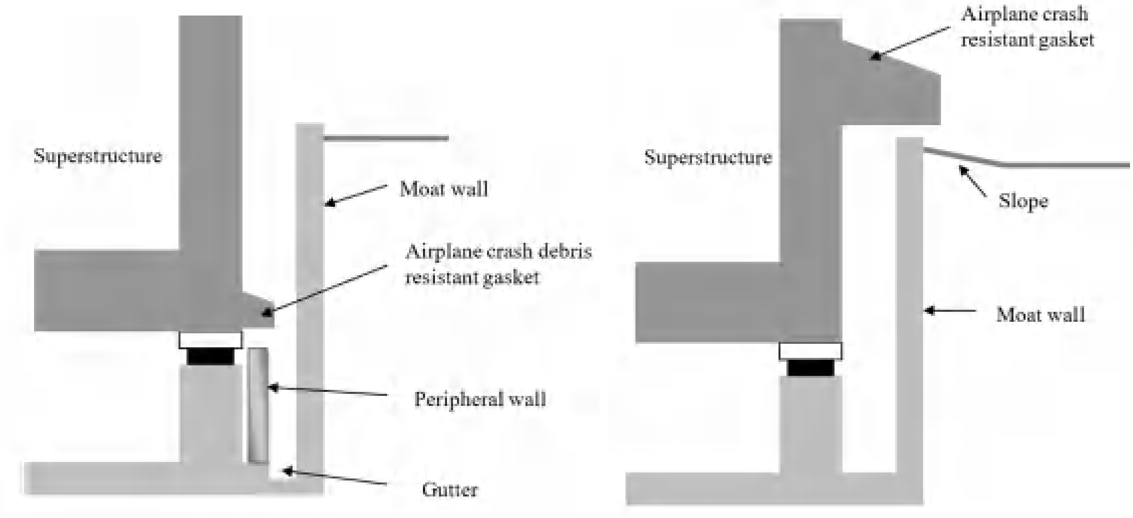

Figure 8 Examples of R&D projects utilising moat protection against airplane crash (provided by Nuvia)

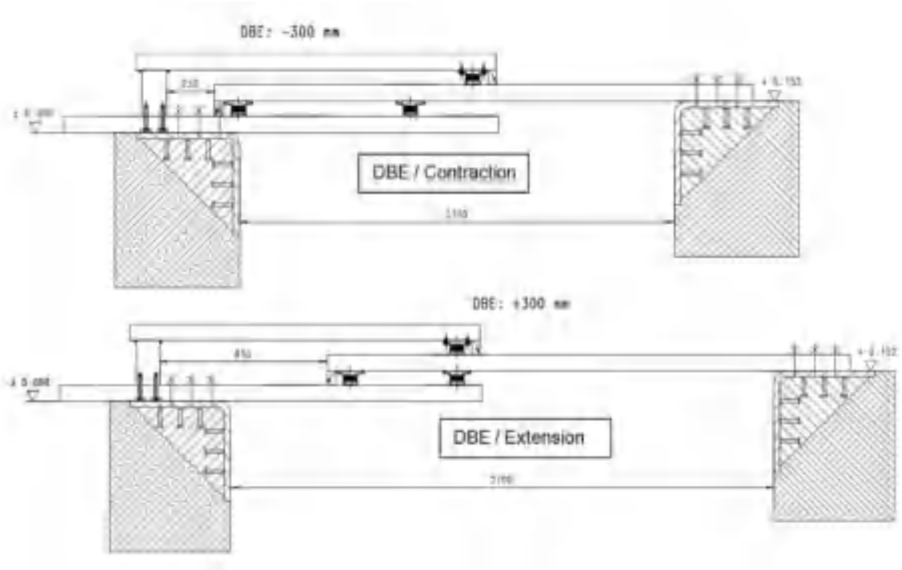

Figure 9 Working scheme of the joint-cover at SILER [34]

Expectations:	
4.6-1	Capacity design of the foundation is expected considering the maximum demand of the bearings which may be limited by the displacement at the stop.
4.6-2	The connections between the bearings and the pedestal shall be mechanically connected and not rely on grout or friction.
4.6-3	The SIS should be protected from external hazards and the use of a moat cap should be considered.

4.7 Superstructure design

4.7.1 Ductility

It is common practice to design any isolated superstructure to remain elastic under DBE shaking to concentrate the energy absorption within the SIS and avoid damage in the superstructure. Yielding of the superstructure increases its fundamental period and can reduce the effectiveness of the isolation. This performance expectation is consistent with the general approach for safety critical structures that they remain elastic under DBE shaking, equivalent to Limit State D in ASCE 43-19 [28].

Research has been conducted on the behaviour of isolated superstructures at higher than design basis demands which demonstrates that the plastic demand on the superstructure is amplified by a greater factor compared to an equivalent non-isolated building [42]. This research shows that the margin to failure and therefore the reliability at design basis is not equal between an isolated and non-isolated building subjected to identical ground shaking. To overcome this issue and provide an isolated solution that is as reliable as a non-isolated structure, then the superstructure should not account for a ductility reduction factor at BDBE and should instead be designed elastically for both the DBE and the BDBE.

It is understood that some designs in the US may allow ductility in the superstructure, equivalent to Limit State C in ASCE 43-19. This would increase the complexity of the analysis but it is considered possible to demonstrate the performance of the NPP and supported SSCs.

4.7.2 Basemat

The basemat is the raft above the SIS and transfers load from the superstructure to the bearings. The basemat is required to be sufficiently stiff so as to uniformly distribute loads to the bearings [11]. Deflections, including short-term and long-term contributions, should be accounted for in the design. The bearings should ideally be positioned to coordinate with the major superstructure elements above. Alternatively, the use of a thick strong basemat above the isolators, as has been used on precedent nuclear facilities, enables flexibility with respect to the isolator locations.

In the event of replacement or failure of a bearing, it is required that the basemat is capable of resisting gravity loads assuming the loss of a single bearing. Multiple load-cases should be assessed, with each one representing the loss a single bearing [11]. Refer to Section 3.3 for the reliability and rationale for this requirement.

4.7.3 Dynamic coupling

The introduction of an SIS increases the fundamental period of the response which will affect the dynamic coupling with supported SSCs. Most SSCs are expected to have a stiff response (with a low period response) so increasing the fundamental period should not introduce coupling effects. However, sloshing periods tend to be longer so increasing the fundamental period is more likely to introduce coupling effects.

In a non-isolated building, the period of the superstructure is usually sufficiently uncorrelated with sloshing periods that these do not instigate resonance within pools causing significant sloshing and overpressure on the containment lids. The sloshing behaviour within a seismically isolated NPP is more complex as resonance may occur when the natural period of the fluid aligns with that of the isolation layer. This topic has been the subject of several research papers published in the last two years but a detailed literature review was beyond the scope of this report.

Some AMR proposals include pools with different arrangements compared to conventional large LWRs and may involve coolants with different densities which will influence their sloshing behaviour. Research into the sloshing behaviour of the pool in a lead-cooled fast reactor was undertaken to determine the effects of seismic isolation [37]. For moderate DBE earthquakes the shift of spectrum closer to the natural frequency of sloshing resulted in higher peak pressures in the tank compared with non-isolated equivalent. At BDBE however, the beneficial effect of the isolation is more significant than the adverse effect of the increase in sloshing.

The full range of variability in the seismic isolation properties should be accounted for when considering dynamic coupling effects. Consideration of only extreme upper and lower bound stiffness properties may not consider the possibility of resonance for intermediate values.

Expectations:	
4.7-1	The superstructure should be designed to remain essentially elastic under both DBE and BDBE shaking.

4.7-2	It is expected that the basemat is sufficiently stiff to transfer the loads, as designed, to the isolators.
4.7-3	The dynamic coupling effects between sloshing periods and the SIS should be assessed.

4.8 SSCs crossing isolation interface

It is necessary to have components which cross the isolation interface and these must be designed to accommodate the maximum relative movement of the superstructure. Particular attention must be paid if safety critical systems cross the interface.

It is necessary to test and qualify all connections and equipment crossing the interface (either physically, numerically or a combination of both) to demonstrate their acceptability [38]. This can be achieved through the development of fragility functions from numerical analysis or demonstrating through testing that there is a sufficient margin to failure. ASCE 43-19 [28] requires that the probability of failure at seismic displacements equal to the CS is 10% or less. Additional consideration is expected for safety critical SSCs in the PSA.

There are a significant number of design solutions available for SSCs crossing the isolation interface, and it is unlikely that widespread bespoke solutions will be required for the expansion joints of pipes, wires and cables [34]. The most critical element entering or exiting a conventional nuclear island is the main steam pipeline which may need a bespoke solution due to its safety classification. For example, orientating two gimbals and one angular joint along the pipeline (with two 90° curves) provides 6 degrees of freedom to the pipeline and allows it to accommodate large displacements of the isolated superstructure. An example from industry is shown in Figure 10.

It is expected that the equipment crossing the interface explicitly accounts for the maximum displacement of the isolation system and that they do not provide restraint which modifies or restricts the isolation system.

Figure 10 Pipeline expansion joints (ambient temperature and pressure) used for seismically isolated tanks in petrochemical plants [34] [41]

Expectations:	
4.8-1	It is expected that SSCs crossing the isolation layer are designed to accommodate the maximum differential displacement of the superstructure at BDBE. Additional consideration is expected for safety critical SSCs in the PSA.
4.8-2	It is expected that SSCs crossing the isolation layer to do not provide restraint or restrict the isolation system.

4.9 Independent seismic peer review

ASCE 43-19 [28] and ASCE 4-16 [29] require an independent seismic peer review for all nuclear facilities including those with a seismic isolation system. The peer review is required to be undertaken by an independent design team with special expertise in one or more aspects of the seismic isolation system.

As seismic isolation is a relatively novel technology within the nuclear industry and generally considered a specialist design, then it is recommended that an independent peer review is considered as part of the design process to validate the assumptions and analysis prior to issuing for regulatory approval.

Expectations:	
4.9-1	The RP should consider undertaking an independent peer review for the analysis and design of the SIS.

5. Specification and testing

SAP EQU.1 [1] requires that qualification procedures are applied to all SSCs to confirm they will perform their allocated safety function in all normal, fault and accident conditions throughout their operational life. As discussed in Section 3, the SIS performs a fundamental safety function and is a non-redundant system [7] which requires a high level of reliability. The qualification procedure should therefore demonstrate the confidence level in the safety case is achieved.

Both European and US standards require bearings to be qualified through testing. The standards do not address qualification of the system as a whole which is discussed further in Section 6.2. The qualification procedure for bearings are based around three stages of compliance.

- Type Testing:

  Type (prototype) testing is used to determine the material properties for each bearing type. These tests are conducted on a small number of bearings and may be used for qualification of products.

- Factory Production Testing:

  Factory production testing is undertaken on the bearings to be installed to provide a high confidence that the bearings have properties within acceptable tolerances to those determined in the type testing. The sampling rate of these tests differs between standards.

- In-service Testing:

  In-service testing is performed on a periodic basis during the operational life of the NPP to assess whether the mechanical properties of the seismic isolation system are within the design assumptions.

The format of testing is similar, however, there are differences in the requirements which are discussed in the following sections.

5.1 Type testing

SAP EMT.3 [1] requires type testing to be carried out before installation and to verify the most onerous conditions for which they are designed. The type testing undertaken for seismic bearings should determine the capacity and in-service properties, including the stiffness and damping properties to be used in design.

Type testing is specified to determine the characteristic properties of both the material (rubber) and the isolation assembly. The tests determine the mechanical properties of the isolator including, but not limited to, the effective shear stiffness and compression stiffness and how each of these is affected by the variables described in Section 4.3.

The test requirements vary between standards BS EN 1337-3 [18], BS EN 15129 [25], ASCE 7-22 [30], ASCE 4-16 [29] and ASCE 43-19 [28]. BS EN 1337-3, BS EN 15129 and ASCE 7-22 are non-nuclear codes and therefore will not be suitable for nuclear applications without supplementary requirements but have been referenced for comparison purposes to demonstrate where enhancements have been made. ENEA guidance [6] published in 2010 described additional requirements that should be considered to supplement BS EN 15129 for nuclear applications. Constantinou [33] also contributed his opinion to the EN 15129 code committee regarding aspects of the code which should be revised. ASCE 43-19 defines the seismic design criteria for SSCs in nuclear facilities which are similar to those required for conventional structures detailed in ASCE 7-22.

The elastomer material testing is described in BS EN 1337-3 Table 1 with the sampling rate included in Table 8. The requirements of the material testing have not been reviewed in detail as the enhancements to the bearing testing are expected to be more relevant.

The testing requirements in ASCE 43-19 and ASCE 4-16 are identical so only ASCE 43-19 will be referred to in this section.

Table 2 Comparison of type testing and factory production control testing requirements in US and European standards

BS EN 15129 cl.	Test	Type Requirements		FPC Requirements		Enhancements to BS EN 15129	
		ASCE 43-19	**BS EN 15129**	**ASCE 43-19**	**BS EN 15129**	**ENEA recommendations**	**Nuclear precedent**
	Minimum number of bearings to be tested	3	2	100%	20%	50%	
8.2.1.2.6	**Compression test (static)**	Not specified.	1.3 x vertical load with no visible defects.	Not specified.	N/A		Increase to 3 x vertical load [45]
8.2.1.2.8	**Compression stiffness**	Not specified.	1/3 x vertical load to service load under seismic.	Not specified.	Within 30% of Type Test value.		
N/A	**Dynamic Compression stiffness**	Not specified.	Not specified.	Not specified.	Not specified.		Enhancement
8.2.1.2.2	**Horizontal stiffness (static)**	Not specified.	Up to design displacement.	Not specified.	Within 20% of adjusted type test value.	Increase to ultimate failure strain or to the distance to the stop.	
8.2.1.2.2	**Horizontal stiffness (dynamic)**	20 fully reversed cycles of loading at the design wind load. 5 fully reversed cycles of loading at a number of increments of design displacement including 25%, 50% 100% minimum earthquake displacements and 100% maximum earthquake displacement. 5 fully reversed cycles of loading at the total maximum displacement.	Strain dependence at design displacement within 20% of design value for strains of 5% (wind), 10%, 20%, 50% and 100% shear strain. Higher levels of shear strain if DBE displacement is greater than 100% shear strain.	5 fully reversed cycles to design displacement with no damage value within 20% of prototype testing.	Stiffness value within 20% at design shear strain.		
8.2.1.2.3	**Horizontal stiffness (dynamic) varying frequency**	Not specified.	Max variation of 20%.	Not specified.	Within 20% of type test value.		
8.2.1.2.4	**Horizontal stiffness (dynamic) with temperature**	Not specified.	Max variation of +80% stiffness for low temperatures and −20% for high temperatures.	Not specified.	N/A	Low temperatures may not be applicable to NPPs.	

8.2.1.2.5	**Horizontal stiffness (dynamic) with repeated cycles (scragging)**	Not specified.	Ratio between the 2^{nd} and 10^{th} cycle is greater or equal to 0.7; Ratio between the 1^{st} and 10^{th} cycle is greater or equal to 0.6	Not specified.	N/A		
8.2.1.2.7	**Horizontal capacity under max and min vertical loads**	Not specified.	No defects observed.	Not specified.	N/A		
8.2.1.2.9	**Horizontal stiffness (dynamic) due to ageing**	Not specified.	Change less than 20% after 14 days at 70°C.	Not specified.	N/A		Additional tests undertaken to establish relationship.
8.2.1.2.10	**Creep test**	Not specified.	Total creep less than 20% between 10 and 10^4 minutes.	Not specified.	N/A		
8.2.1.2.2	**Horizontal stiffness (static)**	Not specified.	Up to design displacement.	Not specified.	Within 20% of adjusted type test value.	Increase to ultimate failure strain or to the distance to the stop.	
N/A	**Horizontal stiffness under tension**	Not specified.	Not specified.	Not specified.	Not specified.		Enhancement.
N/A	**Horizontal stiffness in diagonal direction**	Not specified.	Not specified.	Not specified.	Not specified.		Enhancement.
N/A	**Tension stiffness**	Not specified.	Not specified.	Not specified.	Not specified.		Enhancement. Apply tension to failure reporting stiffness.

Refer to Table 2 for the comparison between ASCE and BS EN requirements. The design of the recent nuclear facilities in France was supported by testing in accordance with BS EN 15129 with additional testing to enhance the code as included in the table. Further information on the type testing undertaken for ITER can be found in paper by Syed et. al. [45].

5.1.1 Prequalification

Prequalification is used in both US and European practice to demonstrate the suitability of the bearings for the application and determine the properties for use in design.

ASCE 4-16 [29] requires the following for qualification of the bearings and the SIS:

- Dynamic testing of full-scale (prototype) isolators for compressive and tensile axial loads and bidirectional horizontal motion at amplitudes of displacement expected for BDBE ground motions.
- Development of verified and validated numerical models capable of predicting the results of dynamic testing of prototype isolators, including deterioration of hysteresis caused by energy dissipation during earthquakes.
- Demonstration through basic chemistry, laboratory tests, and field applications that the mechanical properties of the isolators do not change by more than 20% over a 50- to 100-year period in the temperature range of 4.4°C to 26.67°C.
- System-level testing of the isolation system using three translational components of earthquake ground motion.
- Verification and validation of numerical tools and codes to predict the seismic response of the isolation system.
- Deployment of the isolation system in mission-critical infrastructure.

Prequalification requirements are not specified in the European standards but the requirements listed above are expected to be covered by the safety case for the NPP.

BS EN 15129 [25] defines limits on the similarities between existing products before further type testing is required. For the use on NPPs, it is recommended that only identical bearing components are used if historic product testing is to be used in lieu of project specific testing and that the rubber used for the production batch is tested to demonstrate conformity.

5.1.2 Number of prototype units for testing

BS EN 15129 [25] and ASCE 7-22 [30] only require 2 independent prototypes to undergo each test but these standards are for non-nuclear applications. ASCE 43-19 [28] requires a minimum of 3 independent prototypes to be tested but additional testing allows for less conservative values to be used to achieve the required 90% confidence level. Nuvia’s experience on previous NPPs is to use at least 3 prototypes but preferably 6 for evaluating critical parameters.

BS EN 15129 and ASCE 7-22 only require 3 cycles for the horizontal stiffness test whereas ASCE 43-19 increases this to 5.

It is expected that the confidence level achieved by the testing regime is compatible with the level of reliability assumed in the safety case. A minimum of 3 prototypes is therefore recommended with the benefit of additional tests to be considered to increase confidence in the characteristic material properties.

5.1.3 Full-scale prototypes

BS EN 15129 [25] allows reduced scale prototypes for some of the tests whereas ASCE 43-19 [28] requires full-scale prototypes for all type testing. The ENEA guidelines [6] for enhancing BS EN 15129 recommends that full-scale prototypes are used for NPPs.

Rubber properties vary depending on their dimensions due to changes in the manufacturing process such as the rate of vulcanisation in large bulk rubber compared with smaller samples. Reduced scale prototypes will therefore not have the same dynamic properties as their full-scale counterparts.

The type testing undertaken by Nuvia for the precedent nuclear facilities have all been on full-scale prototypes except for the accelerated ageing tests. The size of the isolators generally used on NPPs mean that there are limited suitable test facilities that are capable of testing full-scale prototypes. This may lead to difficulties in sourcing test facilities for the proposed bearings. The use of reduced scale samples for accelerated ageing tests is considered conservative; refer to Section 5.1.8 for further details.

It is expected that all type tests are undertaken with full-scale prototypes for nuclear applications.

5.1.4 Margin to failure

SAP EHA.18 [1] requires the performance of the building to be assessed under BDB events and to identify the hazard level at which safety functions could be lost. It would therefore be reasonable to expect the hazard level associated with bearing failure to be determined. However, both BS EN 15129 [25] and ASCE 43-19 [28] only require the prototype to be tested up to the maximum design displacement and do not assess the performance to failure.

ENEA recommends [6] enhancements to BS EN 15129 which should include type tests up to failure or instability. However, this is not normally undertaken due to the limitations and potential damage to testing equipment. It is not considered practical to quantify the margin to failure through testing. This is an advantage of implementing a stop, as discussed in Section 4.5, as the bearing displacement is limited to the clearance to the stop.

5.1.5 Comprehensive testing regime

As shown in Table 2, BS EN 15129 [25] provides a more comprehensive, prescriptive testing regime than ASCE 43-19 [28] by fully describing the required tests. It is not specifically noted in ASCE 43-19 which tests should be undertaken to account for temperature, creep or ageing, although cl. 9.2.2.1 implies that these should be accounted for in the project specific testing regime as specified by the suitably qualified design engineer.

A direct comparison between BS EN 15129 and ASCE 43-19 can be made for the horizontal dynamic test where the prototypes are tested at increasing shear strains. The ASCE 43-19 tests are based on percentages of the design displacement while BS EN 151219 refers to shear strain of the isolator. The latter allows for direct comparison between bearings as the test will be undertaken at the same levels of shear strain.

5.1.6 Effect of scragging

The effect of scragging is captured in BS EN 15129 [25] as described in Test ref 8.2.1.2.10 from Table 2. The testing should confirm a maximum change in properties of 40% between the virgin properties and those measured in the 10th cycle.

BS EN 15129 specifies that the 3rd cycle of behaviour should be reported for each test. Constantinou [33] notes that the 3rd cycle typically provides the most stable behaviour for the device when scragging and heating effects have stabilised. The behaviour is also stiffer under the 3rd cycle which is conservative for evaluating forces within the superstructure. However, Constantinou challenges whether manufacturers should be required to demonstrate more consistent properties over the cycles.

The effect of scragging is not specifically accounted for when combining the test results to obtain the upper and lower bound properties. The testing ensures that the behaviour is within expected limits but is not explicitly accounted for in the UBDP or LBDP.

ASCE 43-19 [28] does not include tests for the effect of scragging presumably because the use of bearings with significant scragging effects is prohibited in the US, as discussed in Section 4.3.1.7.

5.1.7 Effect of temperature

The effect of temperature is captured in BS EN 15129 [25], as described in ref 8.2.1.2.4 of Table 2, and is intended to characterise changes in the mechanical properties due to both high and low temperatures. Two tests are specified for the effect of temperature:

- Effect of temperature on the shear modulus and damping, where the sample is stored at the target temperature for one hour. Recommended temperatures of −20°C, −10°C, 0°C, 23°C and 40°C are given.

- Resistance to crystallization, where the sample is stored at low temperature (−15°C) for 7 days.

Nuclear applications can likely neglect the lower temperature conditions as these may not be reached in the more stable environment in the isolation layer compared with bridge bearings which are exposed externally. ENEA [6] recommends removing the tests at −10°C and −20°C but maintaining the 0°C and 40°C tests. However, as testing to BS EN 15129 is prequalifying the bearing for multiple applications it is likely that the low temperature tests will not be removed.

The duration that the isolator is held at an elevated or reduced level is not currently accounted for in the testing regime but has been shown to influence the results [6]. It is recommended that the testing regime accounts for duration at elevated or reduced temperatures.

The acceptance criteria in BS EN 15129 are that the shear stiffness does not vary from the result at 23°C by +80% and −20% at the low temperature and ±20% at the high temperature. The temperatures at which these stiffness variations are measured define the allowable temperature range of the material. Should the operating temperature move outside of these limits then additional protection should be provided. The example shown in Figure 11 demonstrates that the material is within the permitted limits for temperatures between −18°C and greater than 50°C.

Given the challenges described above it is considered beneficial to install the bearings in a conditioned space as required in the US (see Section 4.4.5). Controlling the temperature of the isolation layer would reduce the testing required.

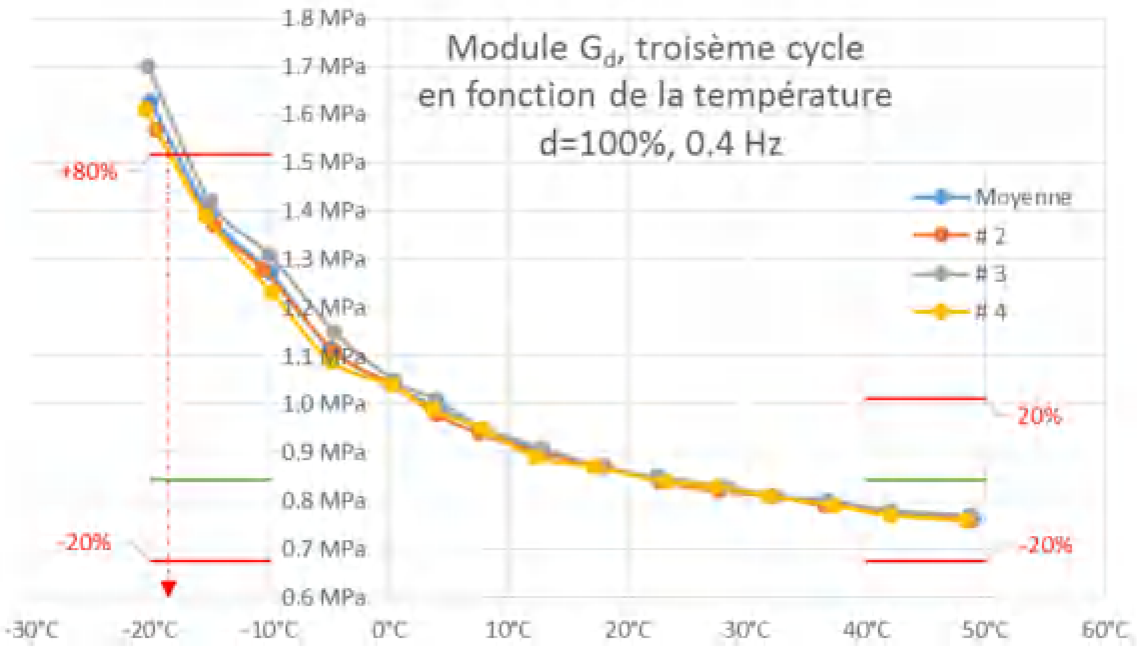

Figure 11 Graph showing the stiffness of bearings with varying temperatures and the BS EN 15129 acceptance criteria at low and high temperatures (provided by Nuvia)

5.1.8 Effect of ageing

The effect of ageing on the dynamic shear modulus and damping is captured in BS EN 15129 [25] as described in ref 8.2.1.2.9 of Table 2. The standard ageing test consists of 14 days at 70°C and must show that the properties change by less than 20%.

This test is not considered to be sufficient to demonstrate the behaviour over the service life of the bearings. For the precedent isolated nuclear facilities additional tests were undertaken at 4 temperatures (70°C, 80°C, 90°C, 100°C) to verify that the ageing mechanism of the rubber can be predicted and provide enough data to establish the law. This extended testing regime can last between 18 and 24 months. (It is noted that BS EN 15129 does not permit the use of an ageing temperature above 70°C).

BS EN 15129 permits the use of test pieces either moulded from the compound cured as far as possible under the same conditions as the bearing or cut from the bearings. It is understood that the test pieces used for the precedent nuclear facilities were cut from the bearings to ensure the curing conditions are the same. However, the size of the test piece will affect the ageing (or continued curing) and must be accounted for in the assessment. It is therefore considered necessary to correlate the results between the test pieces and the full-scale bearings.

It is acknowledged that artificial ageing tests and procedures may not replicate the real ageing behaviour and are more applicable for comparisons to other materials under the same tests [33]. Therefore, the effect of ageing should utilise appropriate field data in addition to artificial ageing to determine predicted properties for design. This is consistent with the qualification requirements for bearings in ASCE 43-19 [28].

The bearings must also be tested in-service to assess the properties and characterise the performance of the bearings during the lifetime of the structure, as discussed further in Section 5.3.

5.1.9 Additional proposed testing

5.1.9.1 Tri-axial seismic excitation testing

The guidelines by ENEA strongly recommend that bearings should be verified using tri-axial tests with real seismic excitations increasing up to failure [6]. This is recommended to verify the bearing behaviour under simultaneous vertical and horizontal loads and high velocity as found in real earthquake ground shaking. The requirement is onerous and has not been adopted on previous NPPs. The authors of the guidance indicate that only two labs in the world can undertake these tests but that difficulty in procuring the tests should not preclude this requirement due to the reliability and safety margin that NPPs demand. It is acknowledged that limited data are available to validate bearing behaviour under real seismic actions and it is expected that dynamic seismic excitation tests are considered to verify the design assumptions. It is also noted that system-level testing of the isolation system using tri-axial excitation is required for prequalification in ASCE 4-16 as discussed in Section 5.1.1.

5.1.9.2 Tension testing

Testing to determine the mechanical properties under tension have been specified on previous isolated NPPs where bearing tension was considered to be possible under BDBE shaking. The tests included horizontal cyclic loading and static tension which are both supplementary to the requirements in BS EN 15129 [25]. However, combining cyclic loading and tension may be difficult given the dearth of testing facilities capable of undertaking the tests. It is expected that tension tests will be specified if tension is predicted by analysis.

5.1.9.3 Diagonal shear testing

Diagonal shear testing at 45° have been specified on the previous NPPs to determine diagonal properties of the rectangular bearings. The asymmetric behaviour of rectangular bearings is a significant limitation and additional testing is expected to determine this effect.

Expectations:	
5.1-1	A minimum of 3 full-scale prototypes should be used for each test and additional testing should be considered to increase the confidence level.
5.1-2	Additional testing and justification should be undertaken to establish the effect of ageing. This is expected to utilise relevant field data and full-scale bearing results.
5.1-3	The designer should justify any differences between the Type testing and the project bearings if standard product testing data is used.
5.1-4	Tri-axial tests with real seismic excitations should be considered to verify the design assumptions (noting limitations and access to testing facilities).
5.1-5	Additional tensile testing is expected if bearings are predicted to go into tension.

5.1-6	It is expected that temperature testing should include investigating the impact of duration of temperature exposure.

5.2 Factory production testing

SAP ECE.3 [1] requires that it can be demonstrated that structures important to safety are free from defects. This can be demonstrated by factory production testing. Factory production testing is carried out to verify that the bearings to be installed on the NPP have properties within the assumed bounds of the prototype tests used in the design and that they do not have defects which may be detrimental to the system's performance.

5.2.1 Test requirements

As shown in Table 2, BS EN 15129 [25] specifies 3 tests to be carried out: compression stiffness, horizontal dynamic testing and horizontal static testing; ASCE 43-19 [28] only requires static horizontal testing.

Both ASCE 43-19 and BS EN 15129 specify that the production tests should apply the design displacement to the bearing. ASCE 43-19 species this to be 5 fully reversed cycles either dynamically at a frequency equal to the isolation system assuming best-estimate properties, or slowly, at a frequency no greater than 0.1Hz. BS EN 15129 indicates the tests should follow the same procedure as the type testing.

5.2.2 Test tolerance

BS EN 15129 [25] requires that the factory production tests do not vary by more than 20% from the type testing but does allow for this to be increased if the designer can suitably demonstrate that this has been accounted for. The tolerance should be explicitly accounted for in the bearing properties used for design, as described in Section 4.3.2.2. ASCE 43-19 [28] does not specify acceptance criteria as these should be prepared by the responsible design professional.

5.2.3 Sampling rate

BS EN 15129 [25] specifies that the first bearing in the production line should be tested along with a random sample corresponding to 20% of the production bearings. The ENEA guidance [6] recommends that this is enhanced for nuclear applications such that a minimum of "50% or more" of the production bearings are tested. ASCE 7-22 [30] and ASCE 43-19 [28] specify that production tests are required on every bearing, equivalent to a 100% sampling rate. This is also understood to be standard practice in Japan. Constantinou [33] recommends that all production devices are tested due to numerous examples of devices and isolators not tested that failed.

The experience on previous NPPs suggests that a 20% sampling rate is onerous for large scale projects with hundreds of bearings. It is understood that a reduced rate was agreed on ITER with the 20% dynamic testing replaced with 33% static testing and 5% dynamic testing. BS EN 1337-3 [18] (Table 5) describes a type testing regime based on the volume of rubber used in the fabrication of the isolators. This methodology was undertaken on ITER for sampling the production bearings, undertaking a static compression test for each 350m^3 of rubber material and a static shear test for each 3500m^3 of elastomeric rubber material [44].

It is acknowledged that it is standard practice in the US and Japan to test 100% of production bearings and that this provides a high level of confidence in the reliability of the bearings that is required for nuclear facilities. It is therefore expected that a sampling rate of 100% is adopted unless a lower frequency can be justified to demonstrate the reliability required.

5.2.4 Quality control

BS EN 15129 [25] requires that the manufacturer is responsible for establishing a factory production control system. This system is considered to satisfy the requirements in BS EN 15129 if it complies with BS EN ISO 9001 [26]. The system consists of procedures, regular inspections and assessment to control the production process.

In the US, quality control procedures for testing and construction of the isolator units and seismic isolation system should follow ASME NQA-1 [31] or an approved equivalent. The SIS as a whole acts as a structural element however individual bearings should also be considered to be mechanical components that are subject to additional requirements of 10 CFR Part 50 Appendix B [16] and RG 1.28 [14].

Independent inspection of the factory production control procedures should be carried out at defined intervals to provide confidence in the procedures.

Expectations:	
5.2-1	The factory production control test tolerance should be defined in the test specification and accounted for in the design properties.
5.2-2	The factory production testing sampling rate is expected to be 100% unless a lower frequency can be justified to demonstrate the reliability required.
5.2-3	A factory production quality control system should be in place that achieves the requirements of BS EN ISO 9001.

5.3 In-service testing

SAP EAD.3 [1] requires periodic measurement to be undertaken where material properties could change over time and therefore impact safety. Both NR and CR are known to stiffen with age as vulcanisation stabilises and ozone attack occurs at the periphery of the bearing. The accelerated ageing tests undertaken during the type testing have known limitations, as described in Section 5.1.8, so it is important to devise an in-service testing regime that can validate the results used in the design.

ASCE 43-19 [28] requires that two spare bearings of each type are stored next to the installed bearings, such that they are exposed to the same environmental conditions, and should be placed under the same average compressive loading as the installed bearings. The spare bearings should be retested every 10 years with the same regime as the production tests undertaken on the bearings prior to installation.

BS EN 15129 [25] does not require in-service testing but the existing isolated NPPs undertake in-service testing of sample bearings. The NPPs have both full-scale bearings and reduced scale samples. The samples are stored within the isolation layer in a specific storage area but are close to the installed bearings and exposed to the same environmental conditions. The samples are positioned within the storage area to minimise the risk of condensation through the lack of natural ventilation. The samples do not need specific maintenance however they should be cleaned before and after use to remove dust and other contaminants. It is important to note that chemical oils or solvents should not be used to avoid elastomer degradation.

The test bearings and samples are required to be kept under permanent compression, representative of the compression found in the bearings. This is achieved through pre-stressing systems individual to each bearing. Due to creep and relaxation in the pre-stressing devices, compression of the samples should be reviewed periodically to reset the devices.

The reduced scale samples are cut from a full-scale bearing so should have similar properties in terms of progress through the vulcanisation process. They have a reduced shape factor compared with the full-scale bearings and it is understood that this gives conservative results for ageing tests due to the increased exposed perimeter of the samples. The representativeness of the samples, and conservativism in the approach was demonstrated on the precedent nuclear facilities by Nuvia at the qualification stage by comparing the evolution of stiffness and damping of reduced-scale and full-scale bearings. Samples are stored both under compression and under no compression to determine how this affects the properties when tested under aged conditions.

It is expected that an in-service testing regime should be developed on bearing samples and full-scale bearings. These tests should be undertaken at least every 10 years during the life of the NPP. The proposed ITER testing regime is to undertake full-scale tests every 10 years and testing on samples every 5 years. Testing will include a static compression test, static shear test, dynamic compression test and a dynamic shear test [44].

Expectations:	
5.3-1	An in-service testing regime should be devised to validate the ageing properties assumed in the design. It is expected that a minimum of 2 bearings for each bearing type should be stored within the isolation layer and tested at 10-year intervals.

6. Installation, inspection, and maintenance

6.1 Installation

The installation of the SIS requires careful management to ensure the bearings will perform as intended. Attention should be paid to the following issues, as described in the IAEA guidance [7] and discussed further within this section:

- Tolerances and geometry of the pedestals.
- Construction sequence is compatible with bearing settlement and rotation.
- Adjustment procedures for the installation of the bearings.
- Grouting and final installation to be carefully executed.

Throughout this section reference is made to the ITER project which represents the latest installation of seismic isolation bearings for a nuclear facility. The approach taken on this project was developed to address the issues discussed above but alternative approaches may also be suitable. The installation procedures must always be adapted to the specific site conditions and environment.

6.1.1 Bearing assembly

To optimise works on site, bearings can be pre-assembled in a factory to control the tolerances on the height, parallelism of the upper and lower anchorage plates, and any gaps between lateral stops and anchorage plates. Factory conditions allow for better quality control and assurance compared with those typically achieved on site.

On the recent ITER project, the bearings were assembled at a factory ahead of the site installation, with the full assembly shown in Figure 12. During the installation process, a controlled force was applied to the bearings to achieve an even distribution of pressure and to ensure a uniform load transfer. The position of the anchorage plates was controlled by adjusting them to ensure they were level and parallel to each other. A non-shrinkage mortar layer was then injected between the anchor plate and the underside of the elastomer to ensure a uniform load transfer between the anchorage plates and the bearing.

Figure 12 Pre-assembled bearing arrangement from ITER project (provided by Nuvia)

As discussed in Section 4.6.2, the horizontal load in the bearings must be transmitted to the structure using mechanical components and may not consider the transfer of load through friction [25]. The Type C bearings in BS EN 1337-3 [18] demonstrate an approach for achieving this, as shown in Figure 13.

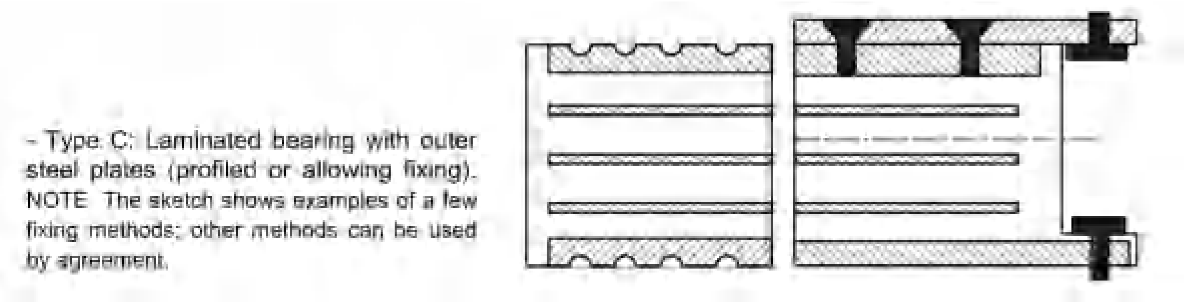

Figure 13 Type C bearing in BS EN 1337-3 [18]

On ITER, no bolts were introduced to the bearing itself, and instead it was fixed to the anchorage plate with bolted removable stops to facilitate bearing replacement. The anchorage plate was then fixed to the pedestal and basemat through the use of shear studs which were embedded during construction, as discussed in Section 6.1.4.

6.1.2 Site installation

Prior to installation, a visual inspection of the bearing assembly should be performed and recorded to check that they were not damaged or deteriorated during transportation and storage. BS EN 1337-11 [21] notes that special attention should be paid to any visible damage, particularly to the corrosion protection, and the security of any temporary clamping devices.

BS EN 15129 [25] and BS EN 1337-11 require site installation of the bearings to be undertaken by a duly trained person, preferably supplied from the manufacturer or working under its supervision. The manufacturer is required to provide detailed installation drawings and procedures, define the installation tolerances and make records of the installation. Construction logistics will need to be considered including providing facilities, dedicated areas and services for carrying out the installation.

The key areas to consider during installation are:

- Quality of casting of anchor plates into the pedestal and basemat.
- Ensuring no voids or bubbles in the concrete/grout below the anchor plates.
- Anchor bolt tightness.

6.1.3 Tolerances

In order for bearings to perform as intended, the installation must meet tight tolerances and this is expected to require special attention. The tolerances should be clearly specified on the installation drawings and communicated to site personnel. In particular, specific attention is expected for:

- Bearing plan location and level.
- Parallelism between the upper and lower anchor plates.
- Bearing verticality.
- Accuracy of the angular distortion.

BS EN 1337-3 [18] allows elastomeric bearings to be either set in mortar or placed directly onto a suitable plinth. In the latter case the plinth surface must achieve a clean and dry surface with requirements on flatness and level.

On ITER, a height adjustment system was incorporated within the pedestal construction to achieve the surface level requirements for the bearings, as shown in Figure 14. Adjustable props were cast within the pedestal which allowed the bearing assembly to be installed and the position of the anchorage plate to be adjusted prior to the final concrete pour of the pedestal. It is understood that the adjustable props provide no structural purpose other than ensuring the surface level requirements for the bearings. The maximum level of the anchorage plate was specified and required to be within ±10mm. The construction sequence is outlined further in Section 6.1.5.

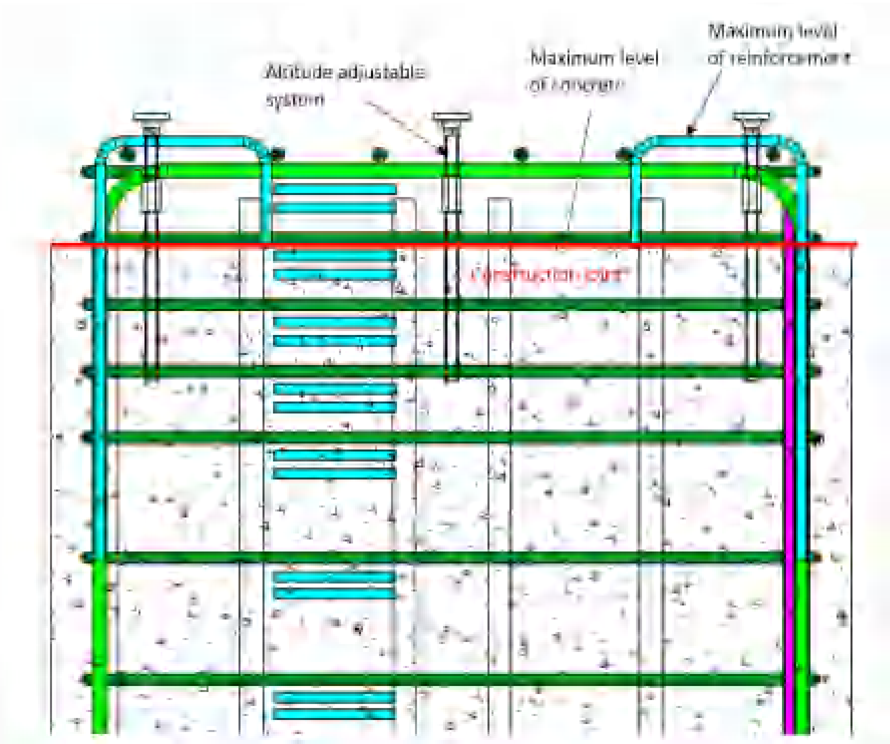

Figure 14 Pedestal detail incorporating height adjustment system (provided by Nuvia)

It is important to control the relative height of the pedestals across the installation of the SIS to ensure the distribution of vertical load to the bearings is as assumed in the design. This is not discussed in BS EN 1337 but the requirements are expected to be included in the specification for the SIS. Settlement of the pedestals under the permanent load condition should be accounted for in these requirements. Ongoing monitoring of foundation settlement may also be required as discussed in Section 6.4.2.

6.1.4 Mock-up

On ITER, a mock-up was requested by the vendor to verify the installation methodology including the ability to achieve the tolerances for the bearing assembly and ensure the concrete was sufficiently compacted with no voids below the anchorage plate. The mock-up included a transparent anchorage plate to verify the compaction below the plate. While a mock-up is not required by the codes and standards this experience demonstrates the perceived challenge of achieving the tolerances and is considered beneficial to provide confidence that these can be achieved.

6.1.5 Construction sequence

The construction sequence can affect the distribution of load to the bearings and the resulting tolerances achieved so should be assessed prior to installation.

The construction sequence was developed on ITER to achieve the required tolerances and involved the following:

1. Cast the pedestal to be within 200 mm of the top including three adjustable props and protruding reinforcement. Retardant applied to top surface to enable the construction joint.
2. Install the bearing assembly onto the adjustable props and level the system.
3. Pour the remainder of the pedestal around the anchorage plates and shear studs.
4. Install formwork and pour the basemat around the upper isolation anchorage plate.

The construction of the basemat must be sequenced to ensure that the bearings are loaded uniformly and in accordance with the design assumptions. ITER utilised temporary load transfer, loading the SIS in a controlled sequence once the basemat was poured and had gained sufficient strength.

Figure 15 Pedestal, isolator and basemat for ITER showing construction joint at the top of the pedestal. Credit: @ITER Organization

Expectations:	
6.1-1	The installation shall be undertaken by suitably qualified and experienced personnel in accordance with a quality management plan.
6.1-2	The tolerances for installation must be specified by the designers and recorded during installation to ensure the bearings will perform as intended.
6.1-3	The installation methodology should allow for adjustability to achieve the tolerances required. The approach should be verified prior to construction and consider the use of a mock-up.

6.2 Commissioning

SAP ECM.1 [1] requires commissioning tests to be defined in the safety case and to be carried out before operating the facility. As the SIS constitutes a safety system it is considered beneficial to undertake commissioning tests to demonstrate that, as built, the design intent claimed in the safety case has been achieved. However, tests of as-built seismic isolation systems do not appear to be undertaken and have not been completed on the precedent nuclear facilities.

There is no requirement internationally to undertake commissioning tests on the dynamic behaviour of the SIS to verify that the bearings will perform as expected under earthquake shaking. A principal inspection of the bearings is carried out at commissioning but this only assesses the condition and static behaviour. Further detail on principal inspections is provided in Section 6.3.2. Continuous monitoring of the structure is recommended in the IAEA guidance [10] which can be used to validate the behaviour of the structure under operation but will not inform the dynamic behaviour before operation. Further detail on monitoring is provided in Section 6.4.

While commissioning testing of the dynamic behaviour of the SIS is considered to be beneficial, it does not appear to be practical to achieve. Instead, the focus should be on the factory production testing of the individual bearings, as discussed in Section 5.2, and the commissioning inspection programme, as discussed in Section 6.3.2.

Expectations:	
6.2-1	Commissioning tests of the SIS as a whole should be considered where reasonably practicable.

6.3 Inspection programme

SAP EMT.2 [1] requires SSCs to receive regular inspection and maintenance and SAP ECE.20 [1] requires that provisions should be made for inspection during normal operation. These safety principles are expected to be addressed through an inspection programme to identify defects and implement repair or replacements where necessary to ensure the performance criteria are consistent with the design.

BS EN 1337-10 [20] provides requirements for both regular and principal inspections. The regular inspection visually checks the condition of the bearings while the principal inspection is more rigorous and should ensure the continued function of the bearing if acted upon where required. The concept of regular and principal inspections has been adopted by the precedent nuclear facilities with further information provided in the following sections.

ASCE 43-19 [28] also requires that an inspection programme is implemented to monitor the isolation system and inspect the individual bearings. It is recommended that this extends to the structure of the basemat, foundation and the moat wall to ensure that any damage does not inhibit the bearings from performing. The standard also requires in-service testing of spare bearings but does not provide specific details of the inspection programme or testing.

6.3.1 Regular inspection

Regular inspections are expected to include the following based on the requirements in BS EN 1337-10 [20] and OPEX provided by Nuvia:

- Condition of the bearing assembly (absence of defects on the concrete infrastructure and in the mortar, capacity for residual movements and absence of any leakage or signs of water).
- Condition of the bearings (absence of irregular global distortion and rotation, absence of bulging or irregular layer shape in the elastomer layers, absence of external rubber cracking, absence of oxidation signs).
- Condition of the bearing plates (absence of defects such as corrosion).
- Result of inspection and whether remedial action is required.

In addition, it is expected that the moat is visually inspected to ensure that movement of the SIS is not restricted.

The frequency of the inspections is not specified in BS EN 1337-10 and should be developed based on the specific details, e.g. bearing type, environmental conditions. Regular inspections have been undertaken on an annual basis on previous NPPs and this testing frequency is considered to be RGP.

6.3.2 Principal inspection

Principal inspections should include all the requirements of regular inspections but with greater detail to allow a detailed assessment to be undertaken. In particular, BS EN 1337-10 [20] requires the deformation of elastomeric bearings to be recorded including vertical and shear deformation on each side. It is expected that a reference document should be produced that constitutes the basis for principal inspections. This document should encompass all measurements taken as well as comments and pictures.

BS EN 15129 [25] requires the first principal inspection to be carried out within one year of the structure being put into service but this is expected to be undertaken prior to operation for nuclear facilities. It is recommended that the first principal inspection is undertaken after all load has been applied to the devices. On the precedent nuclear facilities, the principal inspection is then performed every 5 years. Isolated NPPs in Japan would be required to have principal inspections at 5 and 10 years after construction and subsequently every 10 years [32]. Italian guidance suggests principal inspections should be carried out at 10 year intervals [6].

SAP EMT.8 [1] requires that SSCs are inspected and evaluated following any event that might have challenged their continuing reliability. It is therefore expected that a principal inspection is undertaken after a significant seismic event or fire within the isolation layer. This approach has also been taken on ITER.

In addition to inspections, in-service testing of sample bearings is considered necessary for nuclear facilities as discussed in Section 5.3.

6.3.3 Access for inspection

SAP ECE.8 [1] requires that designs must allow key load-bearing elements to be inspected and maintained. Access for inspection of the bearings must therefore be considered in the design of the isolation layer. This is typically considered as part of the pedestal design.

Expectations:	
6.3-1	The inspection programme should be completed by a suitably qualified person and identify remedial actions if required.
6.3-2	Principal inspections should be undertaken at 5-year intervals and following a hazard event.
6.3-3	Regular inspections should be undertaken on an annual basis.

6.4 Monitoring

6.4.1 Load distribution

It is important to verify that the vertical load in the bearings is in accordance with the design assumptions to ensure that individual bearings do not become overloaded. Instrumentation can be installed within the SIS to allow real-time access to the load distribution. This could be achieved through load cells or strain-gauges in the bearings. Should loads within the bearings fall outside the design limits then additional analysis and verification may be required [11].

It is understood that real-time monitoring of the load distribution in the bearings has not yet been implemented in the precedent nuclear facilities. Instead, the bearings are monitored and surveyed through measurements of the relative displacement between the basemat and the foundation. Real-time monitoring is more critical during the construction stage but the feasibility of maintaining this throughout the operational life is expected to be considered.

6.4.2 Foundation settlement

SAP ECE.24 [1] requires monitoring of settlement for civil engineering structures to check the validity of predictions and provide feedback for design reviews. Foundation settlement is particularly critical for seismic bearings as the movement can affect both the load distribution in the bearings and the rotation of the supports. The analysis and design of the bearings should address both short-term and long-term effects due to anticipated structural movements [11], and, as discussed in Section 4.6 and 4.7, the foundation and basemat should be designed to minimise the effects of differential settlement. ASCE 43-19 [28] also notes that the requirement for the basemat to be designed for the loss of a single bearing enables adjustments to be made should settlement occur.

Long-term foundation deformations and settlements are recommended to be periodically monitored in NUREG/CR 7253 [11] including the relative displacements between the basemat and foundation, the vertical displacement of the foundation and movement of the moat wall. Tiltmeters installed on the lower foundation, basemat and moat walls should be considered to determine whether movement of the moat wall is inhibiting the clearance to the stop [38]. The frequency of the monitoring is not specified but this is expected to be at least every 5 years in accordance with the principal inspections discussed in Section 6.3.2.

6.4.3 Seismic monitoring

The IAEA SSG-67 [10] details the seismic instrumentation to be installed at all NPP sites according to RGP. The purpose of seismic monitoring is to:

- Provide triggering mechanisms for automatic shutdown if the earthquake exceeds a defined threshold.
- Provide alarms to alert operating personnel of the occurrence of the earthquake and provide information for decision making.
- Collect data on the dynamic behaviour of SSCs during an earthquake and assess the degree of validity of analytical methods used in the seismic design and qualification of the buildings and equipment.

The minimum seismic instrumentation that should be included at NPPs is [10]:

- One triaxial acceleration sensor installed to register free field vibrations.
- Three triaxial acceleration sensors installed on the basemat of the reactor building.
- Two triaxial acceleration sensors on representative floors of the reactor building.

The European standards do not include requirements for seismic monitoring of isolated structures. ASCE 43-19 [28] requires that a monitoring programme is developed for isolated NPPs but does not provide any details.

US Regulatory Guide (RG) 1.12 [13] provides guidance on instrumentation in the US context but seismic isolation is beyond the scope of the existing guidance. A proposed update to RG 1.12 states that tri-axial monitoring equipment should be placed at a minimum of three locations around the perimeter of the basemat and up the height of the isolated superstructure to capture the acceleration response including torsional behaviour. It is expected that additional accelerometers are provided on the foundation as well as the basemat in multiple locations to capture the response of the SIS [38].

Expectations:	
6.4-1	Monitoring of the SIS is expected to include the vertical movement of the bearing supports due to foundation settlement at a minimum of every 5 years.
6.4-2	The seismic monitoring equipment should capture the acceleration response above and below the isolation layer with a minimum of 3 locations on plan.

6.5 Replacement

As discussed in Section 3.7, the SIS is expected to have a design life at least as long as the NPP operational life. However, it is possible that bearings will need to be replaced if they become damaged or periodic inspection and testing finds that their properties have deviated significantly from bounding criteria adopted in the design. BS EN 15129 [25] requires that the replacement of the bearings should be possible without resorting to major intervention and BS EN 1337-10 [20] requires that replacement avoids damage to the structure. It is understood to be standard practice in the US to allow for removal and replacement of a bearing.

The earlier precedent NPPs in France and South Africa did not consider the need for replacement during the design, but replacement was required for two bearings at Cruas in 1993. The replacement required the demolition of the pedestal to allow removal which would not be considered acceptable for new NPPs.

It is considered RGP to consider the replacement scenario in the design of the basemat for the loss of any single bearing as well as jacking points to enable the replacement. The governing design case for the basemat is expected to be the vertical load transfer for the loss of any bearing.

The replacement of a bearing does not typically require the shutdown of the reactor based on the experience of the existing precedent NPPs. However, the safety case for the specific project would need to be considered.

The latest installation on ITER provides a 1.9 m high isolation zone to enable access for manoeuvring construction machinery and maintaining personnel access to the isolator from all sides. Replacement of the bearing utilises fixings between removable stops that fix the device in position against the embedded anchor plates, as shown in Figure 16. The sacrificial grout layer between the anchor plate and the bearing can be locally removed to allow the bearing to be replaced. Mock-ups have been used on ITER to verify the isolator assemblies and construction sequence. It is not known whether verification of the replacement strategy was also undertaken at this stage.

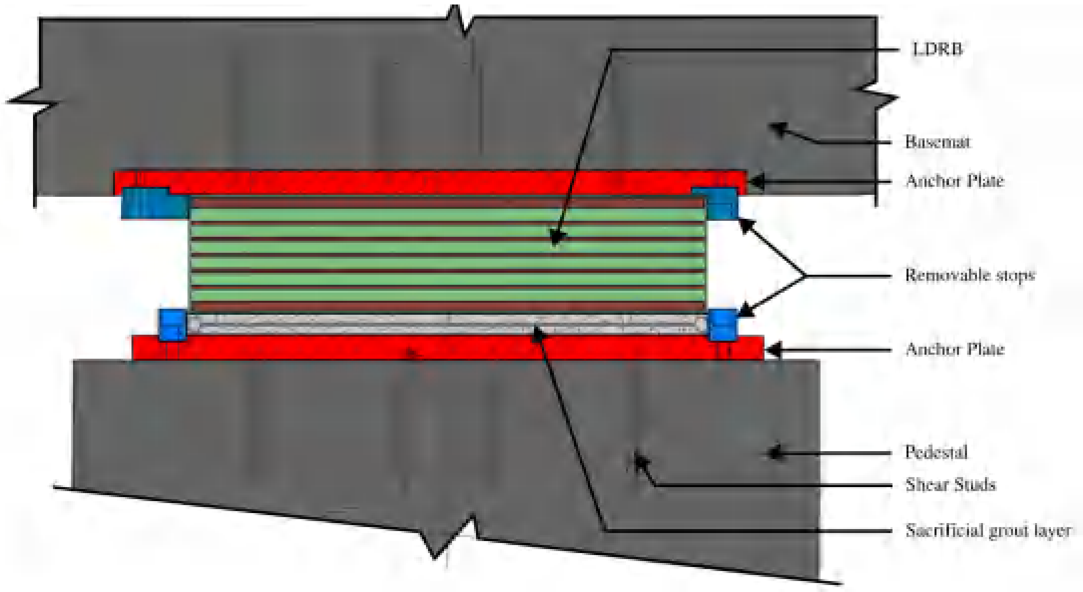

Figure 16 Replacement strategy for bearings installed on ITER (provided by Nuvia)

Expectations:	
6.5-1	Replacement of the bearings should be possible without damage to the structure.
6.5-2	The replacement strategy for the bearings should be developed during the design stage.

7. Recommendations and conclusions

This report documents the research undertaken on the current state of knowledge and RGP for the seismic isolation of NPPs addressing particular challenges associated with proposed SMRs and AMRs. The fundamental requirements for the analysis, design, testing and installation of the SIS have been based on the key SAPs listed in Appendix A. The research has been limited to elastomeric bearings and has focused on the relevant European and US codes and standards which are expected to be used in the UK context.

Seismic isolation has not been implemented on NPPs in the UK before and there is limited precedent internationally. This results in regulatory challenges in assessing the safety case for the use of an SIS on an NPP in the UK. In summary of this research, the following challenges are considered to be the most significant:

- The Eurocode and Euronorms covering the design and testing of anti-seismic bearings are not nuclear specific so are expected to be supplemented and enhanced by the RP to achieve the required reliability. Based on typical nuclear practice in the UK, it is likely that this will be achieved by combining with the US nuclear standards which provide greater detail on the analysis requirements. However, the basis of the standards have significant differences and the compatibility of requirements must be justified. If US standards are adopted then particular care should be taken in ensuring compatibility.
- The BDB hazard is not defined in UK regulatory guidance and the performance requirements of the bearings under BDB shaking are not captured in the European standards. It is expected that the approach for justifying the absence of cliff-edge effects under BDB shaking is developed by the RP.
- Elastomeric bearings are considered to have non-ductile failure modes and are not considered to fail in a safe manner, as discussed in Section 3.3. The use of a stop is one approach to prevent the failure of the bearings under excessive deformation. A stop has not been implemented in the precedent isolated nuclear facilities and there is limited guidance on how to consider the consequences of impact with the stop. The analysis and design approach for considering the effects of impact on the stop and supported SSCs will need to be developed by the RP.
- The performance of the isolated NPP under BDB shaking is expected to be considered as part of the PSA and SAA. The performance of the bearings beyond the tested parameters and the consequence of impact with a stop are strictly beyond the requirements for Civil Engineering and will be difficult to assess with any confidence. The RP should give further consideration of these issues for safety critical SSCs.
- Elastomeric bearings with synthetic rubber may exhibit a higher variability of mechanical properties than those with natural rubber. For this reason, synthetic rubber bearings are prohibited for use in nuclear facilities in the US despite these being used on the precedent nuclear facilities in France. It is critical that the variability of the mechanical properties of the bearings is considered within the safety case of the SIS.
- The variability and reliability of the bearings should be appropriate for the safety classification of the facility and justified in the analysis and design methodology for the SIS. One approach adopted in the US is to limit the variability of the bearing properties to less than ±20% over the lifetime of the facility such that the variability may be considered insignificant in comparison to that in ground motion, soil and structure. Alternatively, the methodology for determining the UBDP and LBDP in the European bearing standards should be developed to achieve the required level of reliability. The seismic analysis methodology of the building and supported SSCs must consider the full range of potential properties to calculate the forces and displacements used for design.
- The European standards provide a more comprehensive testing regime for the bearings than the US standards, but additional requirements are expected for the use on nuclear facilities. The interpretation of the results in calculating the UBDP and LBDP must also be justified considering all mechanisms that may cause variability of the stiffness and damping.
- There are currently no methods for commissioning the dynamic behaviour of an SIS after installation and therefore a greater reliance is placed on the quality control measures on the production of individual

bearings. It is expected that the frequency of factory production testing in the European standards is enhanced and justified based on the required reliability.

- The properties of elastomeric bearings may vary over time due to ageing of the rubber and there are known limitations with the results of accelerated ageing tests used to assess this effect. An in-service testing regime of full-scale sample bearings is therefore expected to be developed in addition to inspections and long-term monitoring. The results of the in-service testing should be compared with design assumptions and corrective action made if required.
- The introduction of seismic isolation will affect supported and surrounding SSCs and the consequences must be communicated with other disciplines. For example, additional verification will be required for the deformation capacity of SSCs crossing the isolation layer.

Further detail on these challenges and how RGP could be achieved for the analysis, design, testing and installation of the SIS have been summarised in a series of expectations made throughout this document. These are repeated and summarised in Table 3 below.

The proposed use of seismic isolation for SMRs and AMRs is currently driving research in this area and it is expected that alternative approaches for meeting RGP will be developed. The following topics of further research are therefore recommended for ONR to stay abreast of technical developments in this area:

- The compatibility of European and US codes and standards has been highlighted as a regulatory challenge for NPPs with seismic isolation but this is a common challenge when using RGP adopted from US requirements. Further research into the reliability basis of the European and US codes and standards would be expected to have a wider application beyond seismic isolation and is recommended for consideration.
- It is understood that the topical report on seismic isolation that is currently under development for the NRC will propose a risk-based approach to define the performance and acceptance criteria based on the core damage risks of AMR technologies. This approach is expected to differ significantly from UK regulatory guidance and is expected to require cross-discipline consideration. It is recommended that ONR review this document when it becomes publicly available later this year.
- This research has focused on the seismic design of isolated NPPs but the introduction of seismic isolation will also affect the design to other external hazards such as radiation, fire, flooding, blast and aircraft impact. Limited guidance is available in the literature reviewed so it is recommended that a detailed review of the latest research is undertaken for these topics.
- It is not anticipated that vertical isolation will be proposed for regulatory assessment in the immediate future due to the significant challenges associated with rocking behaviour and lack of precedents even outside of the nuclear sector. Vertical isolation is more likely to be included on a component level but this level was beyond the scope of this research. Should vertical isolation be proposed on a future NPP in the UK it is recommended that ONR undertake a review of the latest research on this topic.
- It is recommended that ONR engage with the French regulator to discuss how the European standards have been enhanced for the recent nuclear facilities in France and whether there are elements which can be incorporated into UK regulatory guidance.

Table 3 Expectations for implementing seismic isolation on NPPs in the UK

Expectations:	
3.1-1	The safety classification of the SIS should consider the potential of failure to affect the performance and safety function of the supported SSCs. It is expected that the safety classification will be the highest classification used for the supported SSCs.
3.2-1	In the absence of a standard for the seismic design of nuclear facilities in the UK, it is expected that requirements are modified or enhanced to achieve the reliability required, or alternative nuclear-specific standards are used.
3.2-2	ASCE 43-19 and ASCE 4-16 are considered to be RGP for the seismic design of nuclear facilities and it is expected that they will be used to inform nuclear specific requirements and modifications for the analysis and design of the SIS.
3.3-1	The potential failure modes of the SIS must be identified and the consequences of failure assessed to demonstrate that it can fail in a safe manner. It is considered difficult to demonstrate this by providing sufficient margin so alternative strategies are expected to be considered.
3.3-2	The use of a stop is one approach to mitigate the risk of failure of the bearings and allow alternative failure sequences to be designed. Potential cliff-edge effects associated with impact to be considered and SAA.
3.3-3	The design of the SIS should consider the loss of one or more bearings for the horizontal load path and the loss of a single bearing for the vertical load path.
3.4-1	The reliability level or probability of unacceptable performance should be calculated for the SIS and demonstrated that this meets the requirements of the safety case.
3.4-2	The reliability basis of different codes and standards must be considered when combining or enhancing requirements.
3.5-1	The absence of cliff-edge effects in the performance of the bearings under BDB shaking should be considered and justified through testing.
3.5-2	The consequence of bearing failure or impact with the stop should be considered in the PSA and SAA.
3.6-1	It is expected that hazards, other than earthquakes, are considered for the reliability and safety of the SIS and included in the potential failure modes.
3.7-1	It is expected that the SIS is designed for the lifetime of the NPP. The RP may propose otherwise with sufficient justification and methodologies for replacement.
4.1-1	The analysis requirements in ASCE 4-16 are considered to be RGP. It is therefore expected that three-dimensional models using at least 5 ground motions for each of the UB, BE and LB soil properties are analysed.
4.1-2	The analysis methodology should consider the upper and lower bound properties of the bearings.
4.1-3	The modelling of bearings as linear elements should be justified based on relevant test data.
4.1-4	SSI effects should be considered for the design of the substructure. The omission of SSI effects in the design of the superstructure should be justified.
4.2-1	The suitability of synthetic rubbers and HDRBs should be demonstrated in the safety case considering potential changes in mechanical properties throughout the life of the NPP.
4.3-1	It is expected that the range of bearing properties used in design are determined through testing and their sensitivity to the analysis is determined.

Expectations:	
4.3-2	It is expected that the results of the tests are combined to provide upper and lower bound properties to envelope the NPPs seismic performance using a statistical methodology such as that described in BS EN 1990 Annex D.
4.3-3	If the effects of scragging are significant these should be explicitly accounted for in the upper and lower bound properties.
4.3-4	It is expected that the design life of the bearings will be at least the design life of the NPP so that they would not require full replacement during the initial NPP design life.
4.4-1	Tensile stresses in the bearings should be avoided under DBE ground shaking unless testing is undertaken to justify the performance under tension.
4.4-2	The temperature range within the isolation layer should be calculated and the impact on the bearing properties assessed. The use of a conditioned space should be considered to avoid temperatures outside of the range 4.4°C to 26.7°C.
4.5-1	Where a stop has been provided, the clearance to the stop should exceed the BDBE displacement to prevent cliff-edge effects due to impact.
4.6-1	Capacity design of the foundation is expected considering the maximum demand of the bearings which may be limited by the displacement at the stop.
4.6-2	The connections between the bearings and the pedestal shall be mechanically connected and not rely on grout or friction.
4.6-3	The SIS should be protected from external hazards and the use of a moat cap should be considered.
4.7-1	The superstructure should be designed to remain essentially elastic under both DBE and BDBE shaking.
4.7-2	It is expected that the basemat is sufficiently stiff to transfer the loads, as designed, to the isolators.
4.7-3	The dynamic coupling effects between sloshing periods and the SIS should be assessed.
4.8-1	It is expected that SSCs crossing the isolation layer are designed to accommodate the maximum differential displacement of the superstructure at BDBE. Additional consideration is expected for safety critical SSCs in the PSA.
4.8-2	It is expected that SSCs crossing the isolation layer to do not provide restraint or restrict the isolation system.
4.9-1	The RP should consider undertaking an independent peer review for the analysis and design of the SIS.
5.1-1	A minimum of 3 full-scale prototypes should be used for each test and additional testing should be considered to increase the confidence level.
5.1-2	Additional testing and justification should be undertaken to establish the effect of ageing. This is expected to utilise relevant field data and full-scale bearing results.
5.1-3	The designer should justify any differences between the Type testing and the project bearings if standard product testing data is used.
5.1-4	Tri-axial tests with real seismic excitations should be considered to verify the design assumptions (noting limitations and access to testing facilities).
5.1-5	Additional tensile testing is expected if bearings are predicted to go into tension.

Expectations:	
5.1-6	It is expected that temperature testing should include investigating the impact of duration of temperature exposure.
5.2-1	The factory production control test tolerance should be defined in the test specification and accounted for in the design properties.
5.2-2	The factory production testing sampling rate is expected to be 100% unless a lower frequency can be justified to demonstrate the reliability required.
5.2-3	A factory production quality control system should be in place that achieves the requirements of BS EN ISO 9001.
5.3-1	An in-service testing regime should be devised to validate the ageing properties assumed in the design. It is expected that a minimum of 2 bearings for each bearing type should be stored within the isolation layer and tested at 10-year intervals.
6.1-1	The installation shall be undertaken by suitably qualified and experienced personnel in accordance with a quality management plan.
6.1-2	The tolerances for installation must be specified by the designers and recorded during installation to ensure the bearings will perform as intended.
6.1-3	The installation methodology should allow for adjustability to achieve the tolerances required. The approach should be verified prior to construction and consider the use of a mock-up.
6.2-1	Commissioning tests of the SIS as a whole should be considered where reasonably practicable.
6.3-1	The inspection programme should be completed by a suitably qualified person and identify remedial actions if required.
6.3-2	Principal inspections should be undertaken at 5-year intervals and following a hazard event.
6.3-3	Regular inspections should be undertaken on an annual basis.
6.4-1	Monitoring of the SIS is expected to include the vertical movement of the bearing supports due to foundation settlement at a minimum of every 5 years.
6.4-2	The seismic monitoring equipment should capture the acceleration response above and below the isolation layer with a minimum of 3 locations on plan.
6.5-1	Replacement of the bearings should be possible without damage to the structure.
6.5-2	The replacement strategy for the bearings should be developed during the design stage.

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Appendix A

Relevant Safety Assessment Principles

EKP.3	Defence in depth	Nuclear facilities should be designed and operated so that the defence in depth against potentially significant faults or failures is achieved by the provision of multiple independent barriers to fault progression.
ECS.2	Safety classification of structures, systems and components	Structures, systems and components that have to deliver safety functions should be identified and classified on the basis of those functions and their significance to safety.
ECS.3	Codes and standards	Structures, systems and components that are important to safety should be designed, manufactured, constructed, installed, commissioned, quality assured, maintained, tested and inspected to the appropriate codes and standards.
ECS.4	Absence of established codes and standards	Where there are no appropriate established codes or standards, an approach derived from existing codes or standards for similar equipment, in applications with similar safety significance, should be adopted.
ECS.5	Use of experience, tests or analysis	In the absence of applicable or relevant codes and standards, the results of experience, tests, analysis, or a combination thereof, should be applied to demonstrate that the structure, system or component will perform its safety function(s) to a level commensurate with its classification.
EQU.1	Qualification procedures	Qualification procedures should be applied to confirm that structures, systems and components will perform their allocated safety function(s) in all normal operational, fault and accident conditions identified in the safety case and for the duration of their operational lives.
EDR.1	Failure to safety	Due account should be taken of the need for structures, systems and components to be designed to be inherently safe, or to fail in a safe manner, and potential failure modes should be identified, using a formal analysis where appropriate.
EDR.2	Redundancy, diversity and segregation	Redundancy, diversity and segregation should be incorporated as appropriate within the designs of structures, systems and components.
EDR.3	Common cause failure	Common cause failure (CCF) should be addressed explicitly where a structure, system or component employs redundant or diverse components, measurements or actions to provide high reliability.
EDR.4	Single failure criterion	During any normally permissible state of plant availability, no single random failure, assumed to occur anywhere within the systems provided to secure a safety function, should prevent the performance of that safety function.
ERL.1	Form of claims	The reliability claimed for any structure, system or component should take into account its novelty, experience relevant to its proposed environment, and uncertainties in operating and fault conditions, physical data and design methods.
ERL.2	Measures to achieve reliability	The measures whereby the claimed reliability of systems and components will be achieved in practice should be stated.
ERL.4	Margins of conservatism	Where safety-related systems and/or other means are claimed to reduce the frequency of a fault sequence, the safety case should include a margin of conservatism to allow for uncertainties.
ECM.1	Commission testing	Before operating any facility or process that may affect safety it should be subject to commissioning tests defined in the safety case.
EMT.1	Identification of requirements	Safety requirements for in-service testing, inspection and other maintenance procedures and frequencies should be identified in the safety case.
EMT.2	Frequency	Structures, systems and components should receive regular and systematic examination, inspection, maintenance and testing as defined in the safety case.
EMT.3	Type-testing	Structures, systems and components should be type tested before they are installed to conditions equal to, at least, the most onerous for which they are designed.

EMT.4	Validity of equipment qualification	The continuing validity of equipment qualification of structures, systems and components should not be unacceptably degraded by any modification or by the carrying out of any maintenance, inspection or testing activity.
EMT.5	Procedures	Commissioning and in-service inspection and test procedures should be adopted that ensure initial and continuing quality and reliability.
EMT.6	Reliability claims	Provision should be made for testing, maintaining, monitoring and inspecting structures, systems and components (including portable equipment) in service or at intervals throughout their life, commensurate with the reliability required of each item.
EMT.7	Functional testing	In-service functional testing of structures, systems and components should prove the complete system and the safety function of each functional group.
EMT.8	Continuing reliability following events	Structures, systems and components should be inspected and/or re-validated after any event that might have challenged their continuing reliability.
EAD.1	Safe working life	The safe working life of structures, systems and components that are important to safety should be evaluated and defined at the design stage.
EAD.2	Lifetime margins	Adequate margins should exist throughout the life of a facility to allow for the effects of materials ageing and degradation processes on structures, systems and components.
EAD.3	Periodic measurement of material properties	Where material properties could change with time and affect safety, provision should be made for periodic measurement of the properties.
EAD.4	Periodic measurement of parameters	Where parameters relevant to the design of plant could change with time and affect safety, provision should be made for their periodic measurement.
EAD.5	Obsolescence	A process for reviewing the obsolescence of structures, systems and components important to safety should be in place.
EHA.4	Frequency of initiating event.	For natural external hazards, characterised by frequency of exceedance hazard curves and internal hazards, the design basis event for an internal or external hazard should be derived to have a predicted frequency of exceedance that accords with Fault Analysis Principle FA.5. The thresholds set in Principle FA.5 for design basis events are 1 in 10 000 years for external hazards and 1 in 100 000 years for man-made external hazards and all internal hazards (see also paragraph 629).
EHA.6	Analysis	The effects of internal and external hazards that could affect the safety of the facility should be analysed. The analysis should take into account hazard combinations, simultaneous effects, common cause failures, defence in depth and consequential effects.
EHA.18	Beyond design basis events	Fault sequences initiated by internal and external hazards beyond the design basis should be analysed applying an appropriate combination of engineering, deterministic and probabilistic assessments.
EHA.7	'Cliff-edge' effects	A small change in design basis fault or event assumptions should not lead to a disproportionate increase in radiological consequences.
ECE.1	Functional Performance	The required safety functions and structural performance of the civil engineering structures under normal operating, fault and accident conditions should be specified.
ECE.2	Independent Arguments	For structures requiring the highest levels of reliability, multiple independent and diverse arguments should be provided in the safety case.
ECE.3	Defects	It should be demonstrated that structures important to safety are sufficiently free of defects so that their safety functions are not compromised, that identified defects can be tolerated, and that the existence of defects that could compromise safety functions can be established through their lifecycle.
ECE.7	Foundations	The foundations and sub-surface structures should be designed to meet their safety functional requirements specified for normal operation and fault conditions with an absence of cliff edge effects beyond the design basis.
ECE.8	Inspectability	Designs should allow key load-bearing elements to be inspected and, where necessary, maintained.

ECE.12	Structural analysis and model testing	Structural analysis and/or model testing should be carried out to support the design and should demonstrate that the structure can fulfil its safety functional requirements over the full range of loading for the lifetime of the facility.
ECE.13	Use of data	The data used in structural analysis should be selected or applied so that the analysis is demonstrably conservative
ECE.14	Sensitivity studies	Studies should be carried out to determine the sensitivity of analytical results to the assumptions made, the data used, and the methods of calculation
ECE.15	Validation of methods.	Where analyses have been carried out on civil structures to derive static and dynamic structural loadings for the design, the methods used should be adequately validated and the data verified.
ECE.20	Inspection, testing and monitoring	Provision should be made for inspection, testing and monitoring during normal operations aimed at demonstrating that the structure continues to meet its safety functional requirements. Due account should be taken of the periodicity of the activities.
ECE.24	Settlement	There should be arrangements to monitor civil engineering structures during and after construction to check the validity of predictions of performance made during the design and for feedback into design reviews.
FA.1	Design basis analysis, PSA and severe accident analysis	Fault analysis should be carried out comprising suitable and sufficient design basis analysis, PSA and severe accident analysis to demonstrate that risks are ALARP.
FA.2	Identification of initiating faults	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.
FA.3	Fault sequences	Fault sequences should be developed from the initiating faults and their potential consequences analysed.