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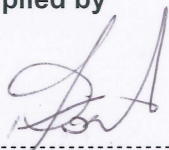
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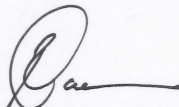


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1. Introduction

The events at Fukushima Daiichi in March 2011 highlighted the need for nuclear power stations to be capable of mitigating the effects of severe external events exceeding their original design basis. Working teams and initiatives were established, by Nuclear Engineering at Koeberg Nuclear Power Station (KNPS), to purchase accident mitigation equipment and implement plant modifications based on the findings of stress tests performed.

This guide was developed to provide the requirements for the design and manufacture of SSCs that are required for Design Extension Conditions (DEC). This guide focuses on the DEC requirements related to seismic events. These requirements are applicable to all SSCs classified to mitigate the effects of DEC seismic events.

2. Supporting Clauses

2.1 Scope

This guide does not replace any of the existing design basis documents. This guide documents the design requirements for modifications and SSC required for DEC specifically focusing on DEC seismic events.

2.1.1 Purpose

The purpose of this guide is to stipulate the seismic requirements for SSC that are specified to mitigate the effects of a DEC seismic event.

The basis of these requirements is provided in Appendix A.

2.1.2 Applicability

This document shall be applicable to Koeberg Nuclear Power Station.

2.1.3 Effective date

This guide is effective from the date of authorisation.

2.2 Normative/Informative References

Parties using this document shall apply the most recent edition of the documents listed below.

2.2.1 Normative

- | | |
|---------------------------|--|
| [1] IAEA, SSR-2/1 | – IAEA Safety Standards, Safety of Nuclear Power Plants: Design, Rev 1, 2016 |
| [2] DSG 318-033 | – Specification for Seismic Qualification of Electrical and Mechanical Equipment |
| [3] JN385-NSE-ESKB-R-5293 | – Nuclear Island Floor Response Spectra |
| [4] JN385-NSE-ESKB-R-5300 | – SEC Pumphouse Response Spectra |

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- [5] JN385-NSE-ESKB-R-5337 – Koeberg Earthquake Site Response off the Nuclear Island
- [6] NRC Reg. Guide 1.61 – Damping Values for Seismic Design of Nuclear Power Plants
- [7] 240-89294359 – Nuclear Safety, Seismic, Environmental, Quality, Importance and Management System Level Classification Standard
- [8] SAR – Safety Analysis Report (Koeberg)

2.2.2 Informative

- [9] NSIP03111 – ESKOM, Duynfontein Site Safety Report, 2015
- [10] 331-93 (rev. 1) – Guide for Classification of Plant Components, Structures and Parts
- [11] 240-121013197 (rev. 1) – Design Extension Related Guidance for Modifications and Equipment – Severe Ambient Temperatures
- [12] 240-120994091 (rev. 1) – Design Extension Related Guidance for Modifications and Equipment – Flooding
- [13] 240-121005755 (rev. 1) – Design Extension Related Guidance for Modifications and Equipment – High-Speed Winds and Tornadoes
- [14] NRC, RG-1.208 – Regulatory Guide-1.208, “Performance-based Approach to Define the Site-Specific Earthquake Ground Motion”, March 2007.
- [15] NNR PP-0014 – National Nuclear Regulator, Position Paper PP-0014, “Considerations of External Events for New Nuclear Installations”, Rev 0, 2012.
- [16] IAEA, SSG-9 – IAEA, Specific Safety Guide No. SSG-9, “Seismic Hazards in Site Evaluation for Nuclear Installations”, 2010.
- [17] PCR, Report No. 07-3835-01 – PCR Engineers & Consultants, Report No. 07-3835-01, “Definition of Design Ground Motion for the PBMR Demonstration Power Plant”, Rev 0, 2008.
- [18] WENRA, Issue F Guidance – WENRA, “Guidance Document - Issue F: Design Extension of Existing Reactors”, 2014.
- [19] ASN, Resolution 2014-DC-0406, et al – ASN, Resolution 2014-DC-0406, 21 January 2014.
- [20] NRC, NUREG/CR-7230 – “Seismic Design Standards and Calculational Methods in the United States and Japan”, 2017
- [21] BCL/CGS/SHRK/18-01 – “Review of the PCR PHSA Study for the PBMR Site at Koeberg”, Bommer Consulting Ltd, Aug 2018.

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2.3 Definitions

Design Extension Conditions – Postulated accident conditions that are not considered for design basis accidents, but that are considered in the design process for the facility in accordance with best estimate methodology, and for which releases of radioactive material are kept within acceptable limits. Design extension conditions comprise conditions in events without significant fuel degradation and conditions in events with core melting.

2.4 Abbreviations

Abbreviation	Explanation
2D	Two-Dimensional
3D	Three-Dimensional
ASN	Autorité de sûreté nucléaire (English: Nuclear Safety Authority) – in France
CGS	Council for Geoscience
D&M	Dames & Moore
DEC	Design Extension Conditions
DER	Design Extension Related
FEM	Finite Element Model
FIRS	Foundation Input Response Spectra
FRS	Floor Response Spectra
GMRS	Ground Motion Response Spectra
HCLPF	High Confidence Low Probability of Failure
IPEEE	Individual Plant Examination of External Events
KNPS	Koeberg Nuclear Power Station
NPP	Nuclear Power Plant
NRC	United States Nuclear Regulatory Commission
NSE	Nuclear Structural Engineering (Pty) Ltd
PBMR	Pebble Bed Modular Reactor
PCR	Paul C. Rizzo & Associates
PGA	Peak Ground Acceleration
PHGA	Peak Horizontal Ground Acceleration
PRA	Probabilistic Risk Assessment
PSHA	Probabilistic Seismic Hazard Assessment
SAR	Safety Analysis Report (Koeberg)
SDE	System Design Engineering
SMA	Seismic Margin Assessment
SPRA	Seismic Probabilistic Risk Assessment
SSHAC	Senior Seismic Hazard Advisory Committee
SSC	Structures, Systems, and Components
SSE	Safe Shutdown Earthquake

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2.5 Roles and Responsibilities

The requirements as stipulated in this guide shall be assigned by Nuclear Engineering through the accurate assignment of classifications and specification development.

The design engineer shall have to identify the specific DEC's for which the SSC is required to mitigate based on factors including its functional requirements, location, and existing barriers.

The classifications and specifications, of the SSCs required during DEC's, are compiled by System Design Engineering (SDE) and authorised by the SDE manager, using the classification process [7].

The requirements as stipulated in this guide shall be incorporated into DER designs by SDE to ensure that the SSC of the design are able to withstand the DEC's.

2.6 Related/Supporting Documents

The latest revision of the classification standard KSA-010, *Nuclear Safety, Seismic, Environmental, Quality, Importance and Management Safety Level Classification Standard (240-89294359)*, makes allowance for the specification of design extension conditions. The classification will specify if the design shall meet the requirements of this guide.

The Dames & Moore (D&M) derived 0.3 g and 0.5 g PHGA earthquake spectra, prepared by NSE, are presented in:

- JN385-NSE-ESKB-R-5293 part 5 for the Nuclear Island, and
- JN385-NSE-ESKB-R-5300 part 5 for the SEC Pump House.
- JN385-NSE-ESKB-R-5337 for the Conservation Centre, TISF and SEP tanks.

The PCR study derived 0.5 g PHGA earthquake spectra, prepared by NSE, are presented in:

- JN385-NSE-ESKB-R-5293 part 12 for the nuclear island,
- JN385-NSE-ESKB-R-5300 part 12 for the SEC pump house,
- JN385-NSE-ESKB-R-5337 for the Conservation Centre, TISF, and SEP tanks.

The D&M derived 0.3 g PHGA earthquake spectra for use in licence basis applications is referenced in DSG 318-033.

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3. Design Extension Condition Requirements

The design requirements for design basis events shall remain unaffected by this guide.

For modifications and equipment that are required to mitigate the effects of a DEC seismic event, the design requirements as specified in this guide shall be utilised. The design codes and standards that will apply to Design Extension Related (DER) SSCs need not comply with the codes and standards specified for Safety Related SSC, if the SSC does not have an SR function. Design codes and standards appropriate for conventional SSCs may be used for DER SSCs (subject to Eskom approval) and will be specified in the designs or specifications based on the SSCs considered.

If SSC carries a design basis seismic classification due to its SR function, or proximity to SR SSC, the design basis requirements shall apply in conjunction with the DEC requirements.

3.1 Seismic Spectra used for Design Extension Related Systems, Structures, and Components

The original design basis Floor Response Spectra (FRS) for KNPS makes use of the D&M 2D Finite Element Model (FEM). This is an older methodology but is still applicable as it is the licensing basis for KNPS.

Nuclear Structural Engineering (Pty) Ltd (NSE) was contracted by Eskom to perform a seismic re-analysis of the KNPS nuclear island and associated safety structures. From these assessments and additional studies, NSE developed additional floor response spectra, using a 3D finite element model, using the PCR seismic hazard assessment as input.

The 3D FEM was developed because a number of restrictions were identified in the representation of the KNPS nuclear island using the original 2D FEM compared to the 3D FEM. These restrictions include:

- a lack of torsional response,
- the generation of FRS on vertical centrelines of the various buildings with no consideration of additional response in the corners, and
- possible over-restraint of the upper raft due to overlapping connections (using rigid elements) between the raft and the underside of the various buildings.

The PCR seismic hazard assessment was used for the DEC seismic requirements as it makes use of the latest regulatory guidelines. The PCR seismic hazard assessment is site specific and produces very different seismic ground motion from the D&M broad-band site independent seismic hazard assessment. For Design Extension Related (DER) SSC, the PCR seismic hazard, in conjunction with the D&M spectra, shall be applied where achievable, see Table 1 for details and Appendix A for the justification.

The D&M spectra shall nevertheless still be used for the design basis of SR SSC as this is part of the licence basis.

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The application of the seismic spectra is detailed in Table 1.

Table 1: Seismic spectra guidance

Description of SSC	Seismic Spectra to be utilised
Safety related SSC, required to withstand the effects of a design basis safe shutdown earthquake (SSE) but <u>not</u> a DEC seismic event.	The D&M derived 0.3 g PHGA earthquake spectra as referenced in DSG 318-033 to meet the plant's licence requirements.
<u>Existing</u> safety related SSC, required to withstand the effects of a design basis SSE <u>and</u> mitigate a DEC seismic event.	<p>The D&M derived 0.3 g PHGA earthquake spectra as referenced in DSG 318-033 will be used to satisfy the safety related requirements.</p> <p><u>AND</u></p> <p>The DEC requirements shall be met by utilising the PCR derived 0.5 g PHGA earthquake spectra.</p> <p>OR</p> <p>If the PCR derived 0.5 g PHGA earthquake spectra model cannot be satisfied by the SSC, the Dames & Moore derived 0.3 g PHGA earthquake as referenced in DSG 318-033 elevated to 0.5 g PHGA may be used.</p> <p>OR</p> <p>The D&M earthquake spectra, using High Confidence Low Probability of Failure (HCLPF) analysis methodology, subject to Eskom approval.</p>
<u>New</u> safety related SSC or safety related SSC being modified, that is required to withstand the effects of a design bases SSE, <u>and</u> mitigate a DEC seismic event.	<p>The D&M derived 0.3 g PHGA earthquake spectra as referenced in DSG 318-033 will be used to satisfy the safety related requirements.</p> <p><u>AND</u></p> <p>The DEC requirements shall be met by utilising the PCR derived 0.5 g PHGA earthquake spectra.</p>
Design Extension Related SSC (<u>not</u> safety related), required to mitigate the effects of a DEC seismic event.	<p>The DEC requirements shall be met by utilising the PCR derived 0.5 g PHGA earthquake spectra.</p> <p><u>AND</u></p> <p>The D&M derived 0.3 g PHGA earthquake spectra¹.</p>

NOTE:

- Methodologies applied to the development and applications of the seismic spectra are subject to Eskom approval.
- The methodologies applied to qualify SSC shall be clearly documented and recorded.
- The spectra damping shall be selected from US NRC Regulatory Guide 1.61 to suit the evaluated SSC.
- For the DEC's, the spectra damping for a SSE shall be selected in the absence of DEC spectra damping, from US NRC Regulatory Guide 1.61, to suit the evaluated SSC.
- For areas where no seismic spectra are available, seismic spectra shall be developed to accurately assess the effects of a seismic event.

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- ¹ The requirement to consider the D&M 0.3 g spectra for SCC that are only DEC related, is purely to address un-conservatism in the PCR studies, highlighted during the independent review of the PCR study. The PGA is under-predicted, particularly in the low frequency range (<10 Hz). While the PCR is also under-predicting in the higher frequency range, the under-prediction is considered less than in the lower frequency range. As the un-conservatism is less in the high frequency range, and only electrical equipment is typically affected in the higher frequency range, it was considered adequate to compensate in the lower frequency range only, by including the requirement to consider the D&M spectra. The anticipated quantity of new DEC electrical equipment to be installed is minimal, before the Duynefontein SSHAC study is completed. The replacement or rework costs if inadequate margin is provided would be significantly less for the electrical equipment, in comparison to re-enforcing civil and mechanical structure and equipment, which are affected at the lower frequencies.

3.2 Development of Floor Motion Response Spectra

3.2.1 SSC off the Nuclear Island

The propagation of the seismic motion from the elevation at which they are defined to the elevation of the structure foundations shall be developed and calculated for projects at the specific locations of interest. These spectra are referred to as the Foundation Input Response Spectra (FIRS). These spectra are localised and shall include site-specific geotechnical properties. The top of bedrock spectra utilised as input motion shall be derived from the guidance presented in Table 1. The development of the FIRS shall be developed using a seismic site response analysis similar to what is used by the SHAKE programme. The spectra developed by NSE and referenced in § 2.6, should be used for comparative purposes when accepting the site specific FIRS.

3.2.2 SSC on the Nuclear Island

The nuclear island is built on bedrock and thus the propagation of the bedrock seismic spectra through the ground is not applicable. The 3D model developed by NSE, referenced in § 2.6, may be utilised for seismic analysis on the nuclear island.

4. Acceptance

This document has been seen and accepted by:

Name	Designation
B. Mashele	Koeberg Engineering Manager
R. Cassim	IPD-K Manager
R. Kearns	IE Manager
R. Goldstein	SDE Manager
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5. Revisions

Date	Rev.	Compiler	Remarks
December 2016	1	M.R. Kearns	Original revision of guide
July 2018	2	N.A.S. Foster	Full revision of document to include basis and incorporate lesson learnt. 1. Included appendix to justify the choice of GMRS. 2. Removed references to NSE. 3. Included guidance regarding use of floor motion response spectra, § 3.2. 4. Provided additional guidance on adopting DEC GMRS. 5. Improved clarity of wording in Table 1. 6. Standardized reference to Rizzo study to PCR study. 7. Reworded to improve clarity, based on feedback. 8. Include insights from an independent external review of the PCR study, performed by Prof. J Bommer.

6. Development Team

The following people were involved in the development of this document:

- N. Foster
- R. Kearns
- J. Venter
- C. Stolle
- J. Austin
- D. Lee

7. Acknowledgements

Not applicable.

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Appendix A Justification of DEC Seismic Spectra

A.1 Introduction

As part of defence in depth, the IAEA has updated its safety requirements and expects that analysis of design extension conditions (DEC), to be undertaken [1] with the purpose of further improving the safety of the nuclear power plant by:

- enhancing the plant's capability to withstand more challenging events or conditions than those considered in the design basis;
- minimising radioactive releases harmful to the public and the environment as far as reasonably practicable, in such events and conditions.

The purpose of introducing DEC seismic spectra is in order to enhance the plant's ability to withstand a seismic event more challenging than the safe shutdown earthquake, in line with IAEA design standard IAEA SSR-2/1, "Safety of Nuclear Power Plants: Design" [1] in particular requirement 20 which states:

"A set of design extension conditions shall be derived on the basis of engineering judgement, deterministic assessments and probabilistic assessments for the purpose of further improving the safety of the nuclear power plant by enhancing the plant's capabilities to withstand, without unacceptable radiological consequences, accidents that are either more severe than design basis accidents or that involve additional failures. These design extension conditions shall be used to identify the additional accident scenarios to be addressed in the design and to plan practicable provisions for the prevention of such accidents or mitigation of their consequences if they do occur."

The main technical objective of considering the design extension conditions is to provide assurance that the design of the plant is such as to prevent accident conditions not considered in design basis conditions, or to mitigate their consequences, as far as is reasonably practicable."

A unique challenge in selecting a seismic DEC for the Koeberg plant is that a Senior Seismic Hazard Analysis Committee (SSHAC) Level 3 study is currently underway to re-characterize the seismic profile of the site, is anticipated to be finalised in toward the end of 2021. Ultimately, the design extension condition seismic event should be based on or evaluated against the SSHAC study in order to ensure that we comply with the NNR position paper PP-0014 [15] and are in line with international regulatory standards (e.g. US-NRC RG-1.60 and RG-1.208). However, in order to progress with post-Fukushima modifications, and minimize the risk of unnecessarily over- or under-designing, it is necessary to develop an interim position based on the best information currently available.

The intent of this appendix is to provide the basis of the DEC seismic requirements as prescribed in Table 1. Without currently having any site-specific seismic study that meets all the requirements of at least a SSHAC Level 2 study, the position outlined in this report, intends to make the best use the site-specific information currently available.

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A.2 Historical Background to Seismic Studies conducted for Duynefontein Site

The currently available seismic hazards studies conducted for the Duynefontein site, are listed below:

1. A series of studies conducted by US consultancy firm D&M between 1973 and 1981, culminating in a 1981 report that defined the seismic design basis for the current Koeberg Nuclear Power Plant.
2. A series of studies conducted by the Council for Geoscience (CGS) for potential nuclear sites in South Africa, including Duynefontein, Bantamsklip, Brazil-Shulphfontein, and Thyspunt. These studies included the seismic baselines established in the so-called SRAFA document (CGS, 2004) and many subsequent studies performed by CGS. These studies were not accepted by the NNR.
3. The probabilistic seismic hazard analysis (PSHA) performed for the PBMR site by PCR (2008) [17].

The D&M (1981) study was completed more than 30 years ago, and significant advances have been made in the intervening decades, both in terms of seismic hazard practice in general and in the knowledge and understanding of the tectonics and seismicity of South Africa. The methodologies employed have been superseded and would no longer be licensable in South Africa or internationally. The Newmark-Hall seismic ground motion response spectra that it produced are based on seismic events that occurred in the Western USA, which is underlain by soft crustal rock in the vicinity of large tectonic seismic sources. More recent seismic data collection indicates that spectra developed for hard rock, low-medium seismicity sites similar to Duynefontein have different shape seismic response spectra primarily due to the magnitude of seismic sources and the fact that the site is situated on hard rock (as opposed to soft crustal rock). In addition, uncertainties were not considered in the original study, which is a critical aspect of current seismic hazard studies.

In 2004, a series of studies was conducted for numerous existing and potential nuclear sites. An independent international review was critical of the approach used in these CGS seismic hazard assessments, and recommended that it should adopt procedures that are consistent with current best practice. The NNR review concluded that a number of fundamental geological, seismological, and geophysical siting factors required to justify the seismic hazard assessment for the PBMR demonstration plant on the Koeberg site, had not yet been addressed in the studies. None of those studies were developed to a level that would be considered a comprehensive and complete site-specific hazard assessment, as confirmed by the NNR review of the PBMR hazard assessment. While this work was effectively abandoned, any new seismic hazard assessment for the site should make extensive use of those elements of the CGS work that usefully inform such a study. Subsequently, both Eskom and CGS has embraced the SSHAC Level 3 process, which they are involved in for both the Thyspunt site which is now complete and the seismic hazard study currently underway for the Duynefontein site.

The most recent seismic hazard study [17] for the site was conducted by PCR, specifically for the PBMR following the non-acceptance of the CGS seismic hazard assessment for the Koeberg site. The PCR study is generally considered an improvement on earlier hazard assessments for the site. The significant improvements being the development of logic trees to capture epistemic uncertainty in the calculation of the hazard in the hard bedrock, and then convolving these rock motions with estimates of site amplification, to obtain the final estimates of the surface motions. The site amplification functions were calculated using Approach 2B of NUREG/CR-6728, using randomised shear wave velocity profiles for the near-surface layers. The PCR study also used US-NRC RG 1.208 and ASCE 43-05 as the basis for the PSHA, and essentially uses a SSHAC Level

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2 approach. However, despite these positive aspects, the report does lack in several respects in terms of being suitable for a state-of-the-practice PSHA, on which to base a nuclear licensing application for a new plant. At the time the study was produced, no evidence of an independent peer review was conducted. A recent independent review [21], conducted by Prof. J. Bommer, the technical lead for the Duynfontein SSHAC Level 3 Study currently underway, concluded that the PCR study does fall short in some areas.

The key concern relates to the lack of a peer review process, the lack of supporting documentation, and its treatment of epistemic (modelling) uncertainty, which is typical of a SSHAC Level 3 approach. Some specific modelling concerns were also identified, such as the method of defining the site's surrounding seismicity zones and possibly other technical assumptions, which are anticipated to result a potential underestimation of the seismic intensities at the site. The primary technical concerns involve the regional seismic zoning assumption that adopts a single optimistic zoning approach, and there is no consideration of the off shore earthquake. With the same seismic input dataset a SSHAC Level 3 methodology will result in an increase the ground motion response spectra. In addition, there are inconsistencies that indicate an under-prediction of the maximum magnitude that could occur in the Ceres area. This will result in an under-estimation of the ground motion in the lower frequency range of the seismic spectra, as the high frequencies motion will be attenuated out over a long distance.

The PCR study does specifically cite RG 1.208 as being the guidance followed for the PSHA it performed. It emphasises the need to include epistemic uncertainties, normally requiring the interpretations of available geological, geophysical, and seismological data in the source region by multiple experts or a team of experts. However, the report does not clarify how expert assessments were made, and it is unclear whether the report was independently peer reviewed. While the report refers to a planned expert panel review, it is unclear and appears doubtful if such a review was ever ultimately performed.

The review concluded that PCR produced design spectra which are not of an adequate standard to be used to update the licencing basis or design a new nuclear facility. However the reviewer supported using the PCR study and spectra as interim input into DEC applications, as it is considered to be more reflective of the site's actual seismic characteristics than the existing D&M design base spectra.

A.3 Justification for Selection of the Interim Seismic Design Extension Condition

None of the existing site-specific seismic studies or PSHA meets all the guidance included in the NNR's PP-0014. As such, none of these existing studies are suitable to update the current licence basis, or in this particular case, the design basis SSE. PP-0014 explicitly states that a site-specific PSHA should be undertaken to quantify the ground motion hazards using a number of evaluation methods accepted for industry practice such as the SSHAC process, or the performance approach provided in US NRC Regulation Guide RG 1.208 [14]. The PCR study used RG 1.208 as guidance to develop the PSHA, but does not meet all the requirements of a SSHAC Level 3 process.

However, due to the current lack of a recent fully licence-compliant seismic hazard assessment, it is necessary to develop a suitable interim position on which to base the DEC seismic criteria. The seismic characterisation of the site has three primary components, namely the seismic spectra shape, a scaling factor to represent the seismic intensity, typically peak ground acceleration (PGA), and a vertical/horizontal ratio, which characterises the vertical motion in terms of the horizontal motion.

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The D&M study uses a broad-band site independent Newmark-Hall spectra shape, which was developed based on the seismic recordings in the Western USA, which is underlain by soft crustal rock, and exposed to large tectonic earthquakes. This seismic spectra shape has high amplitudes at low frequencies, and lower high-frequency amplitudes, which are no longer considered typical of hard rock sites in low to medium seismicity region such as the Central and Eastern USA and our site. The D&M study assumes a 2/3 vertical/horizontal (V/H) ratio, in line with the USA regulatory guidance at the time. This resulted in the plant's SSE being defined with a peak horizontal ground acceleration of 0.3 g (which is also the scaling factor for the Newmark-Hall spectrum), and a peak vertical ground acceleration of 0.2 g. More recent measurements indicate that the V/H is variable over the range of frequencies. This has resulted in PCR study developing a more variable but higher V/H ratio over the range of frequencies, which is generally above 1 and up to 2 in the higher frequency range.

The PCR study developed a uniform response spectrum and a design basis GMRS using PSHA techniques for the site. The SSHAC team for Duynfontein anticipate that their SSHAC study will produce seismic spectra with a shape similar to that developed in the PCR study. The major uncertainty involves the magnitude or amplitude of the curve due to different zonal models, the inclusion of additional alternative methodologies, and the additional site geo-technical investigation.

A.4 Basis for adopting a DEC PHGA of 0.5 g

There is worldwide recognition that there is a small probability that earthquakes may occur in the vicinity of a nuclear power plant (NPP) site that can produce ground motions that exceed the design basis earthquake ground motion of the site. Several nuclear power plants have already experienced a seismic event beyond their seismic design basis (see Appendix B). Notable beyond-design-basis seismic events have occurred at North Anna (0.27 g), Fukushima (0.56 g) and Kashiwazaki-Kariwa (0.7 g) nuclear power plants. On the positive side, it is clear from the recent good seismic performance of Japan's NPPs, when subjected to larger than design basis earthquake motions, that significant safety margin was introduced into the design process [14].

Internationally, it is now generally a regulatory requirement to evaluate NPPs for ground motions greater than the design basis motions. This is in order to provide confidence that there is no "cliff edge" effect (i.e. that ground motions slightly greater than the design basis motions do not lead to significant failures in the plant), and to demonstrate that the risk for potential seismic sources is acceptably low [20]. Plants in the USA have all undergone seismic evaluation to demonstrate they can withstand seismic events beyond their seismic design basis, on instruction from the NRC. The Japanese Nuclear Safety Commission (NSC) also recognizes the possibility of beyond-design-basis earthquake ground motions occurring and refers to the potential consequences as "residual risk." Consideration of this "residual risk" is now a requirement, and re-evaluations of existing plants are ongoing. It is understood that larger ground motions may need to be considered.

Although the seismic design basis of these NPPs have demonstrated significant safety margin in their design, there has nevertheless been numerous beyond design-base seismic events at NPPs. This provides empirical evidence that indicates that the characterisation of extreme seismic events in any region is subject to significant uncertainty, and can lead to under-estimations. There have subsequently been significant improvements to the methodologies used to determine the seismic characterisation of nuclear power plant sites.

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In the USA the evaluation of beyond-design-basis ground motions has been conducted for all operating NPPs in the Individual Plant Examination of External Events (IPEEE) programs. In the IPEEE programme, nuclear licensees conducted either a seismic probabilistic risk assessment (SPRA) to determine a point estimate of core damage frequency or a seismic margin assessment (SMA), which could be either deterministic or probabilistic. The target in either case was to demonstrate a high confidence of low probability of failure (HCLPF) value of 0.3 g PGA for most sites, and 0.5 g PGA for a few sites in higher seismicity areas.

For new nuclear power plants to be licensed in the USA, a seismic margin of 1.67 times the design basis ground motion is required to be demonstrated. While a PRA-based SMA can be used during the initial design and licensing process for new reactors, a seismic PRA must be completed prior to loading fuel in a new nuclear plant. For SSCs located in the balance of the plants that are designed to site-specific ground motions, i.e. the ground motion response spectrum (GMRS), the same requirement is imposed. That is, a plant level HCLPF (high confidence of a low probability of failure) shall be demonstrated to be at least 1.67 times the design basis earthquake motion (GMRS). This requirement may be satisfied by demonstrating that these SSCs individually satisfy the requirement of HCLPFs at least 1.67 times the GMRS. However, the requirement is for the overall plant HCLPF to be at least 1.67 times the GMRS, not for each individual SSC [20].

In France, through a set of resolutions [19], dated 21 January 2014, the French nuclear regulator (ASN) defined the seismic hazard response spectrum to be adopted for SSC of their hardened safety core (i.e. the dedicated systems used to prevent and mitigate core damage in a DEC event), to be higher than a response spectrum defined by the criteria below:

- encompasses the safe shutdown earthquake (SSE) for the site, plus 50%;
- encompasses the probabilistic site spectra with a return period of 20 000 years; and
- takes into account the particular site effects, in particular the nature of the soil, in its definition.

In the South African context, there is no explicit guidance regarding the method of defining a seismic DEC envelope. However, the NNR does provide some guidance in PP-0014, with respect to addressing beyond-design-basis conditions, now referred to as design extension conditions. In order to address beyond-design-basis conditions, the NNR specifies that sufficient margin be provided and “cliff-edge” effects be avoided in the design of the plant. In order to achieve this goal, PP-0014 now includes seismic target safety goals, such as 5×10^{-6} /year target for seismically induced core damage. With these proposed target safety goals, PP-0014 indicates that a seismic margin of approximately 1.7 should be achieved, which is considered to be in line with international requirements.

South Africa is not close to any tectonic boundary where typically large earthquakes are experienced. However, very high peak ground accelerations have been measured during large intra-plate earthquakes elsewhere in the world. As such, it is difficult to put a generic upper enveloping limit even on intra-plate seismic events, which would be reasonable to design to. The systems, designed or strengthened, that are required to mitigate a DEC seismic event should nevertheless be able to cope with the maximum plausible event that could happen at KNPS.

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Based on the above inputs, it is considered reasonable to adopt a DEC intensity factor increase of 1.67 as the design basis scaling factor for PHGA. This results in seismic DEC being defined at 0.5 g PHGA. Adopting a seismic DEC with a PHGA of 0.5 g, provides confidence that the plant could survive most historical seismic events that have been experienced at nuclear power plants to date, including most events from known high-seismicity areas such as Japan. As the Western Cape is considered a low-to-medium seismicity region, while unquantifiable, it does provide additional confidence that the proposed 0.5 g PHGA, should provide reasonable margin to cope with the worst plausible seismic event foreseeable at the Koeberg site. This is comparable or enveloping of the USA and French positions, in line with expectation outlined in the NNR position paper PP-0014, as well as considered adequately enveloping of historical seismic events that have occurred at other nuclear plants.

Based on international OE and the results of the Koeberg limited-scope SMA, the Koeberg existing plant design is generally expected to be able to withstand a seismic event of this intensity. The SMA, provides confidence that the existing plant's seismic margin, which the original seismic codes provided, will generally be adequate to handle a 0.5 g PHGA seismic event, provided the few identified seismic vulnerabilities are resolved.

A.5 Basis for preferring the Uniform Hazard Spectrum

Currently, there are two existing site seismic hazard studies that have potentially usable ground motion response spectra that could either be scaled or adopted for a seismic DEC GMRS. The D&M SSE GMRS could be scaled by a factor of 1.67 to 0.5 g, or the PCR uniform hazard spectra (UHS) for a 100 000-year return period adopted, which has a PHGA of approximately 0.5 g at 100 Hz. The PCR study indicates that 100 Hz is the frequency where the PHGA for the UHS is defined.

The Newmark-Hall seismic ground motion response spectra (GMRS) used in the original D&M studies, was developed in the early seventies, and was based on the most seismically recorded region in the world at the time, California. Since the 1970s, the cumulative measured seismicity recorded has been expanded to many more regions. This has shown that the Newmark-Hall spectral shape is not the most appropriate spectra shape for low-to-medium seismicity sites, underlain by hard rock. While some USA regulatory guides still use similar spectra, based on the Newmark-Hall spectra as a site independent spectra for the design of NPPs prior to siting, the alternative RG1.208 approach should be applied to the site-specific seismic evaluation of NPP sites.

It has now been established that the GMRS shape is primarily a function of the surrounding geology, the maximum potential seismic event magnitude and appropriate ground motion attenuation equations. The Western Cape is significantly different to the West Coast of USA, in that it is not close to any large capable tectonic faults. Duynefontein is underlain by Neoproterozoic rock of the Malmesbury Group which has been measured (i.e. shear wave velocity greater than 1 500 m/s) and classified as hard rock, and is situated in a low-to-medium seismic region. This is more similar to the characteristics of the Central Eastern USA. For a site such as Duynefontein, the Newmark-Hall spectrum is anticipated to over predict the ground acceleration at low frequencies, but under predict the ground acceleration at high frequencies (>10 Hz).

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The PCR study includes GMRS with a uniform mean annual probability of exceedance over all vibrational frequencies (Hz) for the Duynefontein site. It also considers that the site is underlain with hard rock, and is situated in low-to-medium seismicity region. Its GMRS are developed using the PHSA methodology, using NRC Regulatory Guide 1.208 as guidance. As such, the Council of Geoscience, Nuclear Sites Group, as well as the lead for the SSHAC study for Duynefontein (which is currently in progress) have all indicated that the resultant GMRS SSHAC spectra are anticipated to be similar to the uniform hazard response spectra developed in the PCR study. This opinion is largely based on the similarity of the PHSA methodology adopted in both studies, the consideration of Duynefontein being underlain by hard rock, and is situated a low-to-medium seismicity region.

While the current plant licensing basis is still based on the Newmark-Hall spectrum, there is a high degree of confidence that the SSHAC study will result in a spectral shape that is better represented by the uniform hazard spectra developed in the PCR study. Adopting the scaled Newmark and Hall GMRS, in the interim for DEC SSC, is likely to lead to overdesign in the low-frequency range and under design in the high-frequency ranges. The UHS spectra shape, developed in the PCR study, implicitly endeavours to ensure a far more consistent safety margin across all frequencies for the anticipated new design basis spectra.

The major concern regarding the PCR study is that it has not had an independent external review, which clearly does not meet the regulatory—or SSHAC—requirements for an independent or peer review. However, the intent is to use the spectra for an interim period until the SSHAC study is finalized, and to only use it for DEC-related plant enhancements where less stringent requirements could be considered acceptable. While it is generally accepted that the DEC design and analysis requirements should adopt a best estimate approach, and can be less conservative; specific guidance on what this means is currently sparse. The best available known guidance for conducting DEC related analysis is provided by the Western European Nuclear Regulators Association (WENRA).

The WENRA guidance [18] for DEC analysis states that analysis should rely on methods, assumptions, or arguments that are justified, and not be unduly conservative. These methods can be more realistic than for design basis accidents, including best estimate. In addition, it explicitly states that modified acceptance criteria may be used in the analysis. The guidance also clearly states the any DEC analysis should be auditable, paying particular attention where expert opinion is utilized, and take into account uncertainties and their impact. However, it also states that in principle, it could be admissible to perform an analysis without considering uncertainties, while recognising that the consideration of uncertainties is useful to ensure that the results of a best-estimate analysis constitute a meaningful basis for the planning of reasonably practicable improvement measures.

While arguably only indirectly relevant, it is generally accepted international practice that the equipment utilised for the prevention and/or mitigation of DEC can be of commercial grade. Using the spirit of this general DEC practice, it could be argued that supporting analysis/studies may be of an equivalent quality. The argument can easily be made that the review level required of supporting seismic studies need only reflect that of a commercial grade study.

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Using the above guidance, it is not unreasonable to conclude that, while the level of review conducted for the PCR report is not adequate for revising the seismic design basis (SSE licensing basis), a less stringent level of review could be considered permissible for DEC GMRS. Additionally, this will be an interim position that will be revised when the comprehensively reviewed Duynfontein SSHAC study is finalised. The purpose of adopting interim seismic DEC design criteria is to be able to proceed with DEC related plant enhancements utilizing the best seismic information currently available, until the more comprehensively reviewed SSHAC study is completed, and to minimise the risk of unnecessary future rework.

In order to ensure that the financial risk around the uncertainty of the final ground motion response spectra that will be produced by the SSHAC process is minimized, it is considered prudent to adopt the PCR spectra as the interim position. Adopting the Newmark-Hall spectra is likely to result in the overdesign of SSCs affected by low frequencies such as civil structures, while under-designing for equipment affected by higher frequencies, such as electrical equipment. This approach should minimise the risk of unnecessary expenditure in certain areas, while minimizing the risk of having to do future seismic strengthening in others once the SSHAC study is finalized.

A.6 Vertical/Horizontal (V/H) Ratio

Vertical design ground motions (response spectra and time histories) should be developed by using the same methods used for developing horizontal ground motions. Where vertical attenuation relationships are not available, a prescribed ratio between vertical and horizontal ground motion is often used. Both the D&M and PCR studies derive the vertical ground motions, directly from the horizontal ground motion response spectra, using a V/H ratio.

Empirical evidence has shown that the vertical to horizontal ratio typically varies from 0.5 to over 1. The empirical evidence is that the V/H ratio is largest for large magnitude earthquakes, close distances, and in the high frequency range [16]. The D&M studies adopt a constant V/H ratio 2/3 across all frequencies; however, more recent empirical seismic records indicate that this is not conservative, especially in high-frequency ranges.

The PCR study predicts higher V/H ratios that vary over the entire frequency range. The V/H ratio ranges it determined vary between 1 and 2 across the full range, which is more conservative than the D&M's constant $\frac{2}{3}$ assumption. As such, adopting the PCR vertical spectra will incorporate a more conservative and up-to-date V/H ratio assumption. If the scaled D&M approach is adopted, equipment sensitive to elevated vertical acceleration could be under-designed, further supporting adopting the PCR study's UHS as the better choice of interim spectra.

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Appendix B Significant Seismic Events at Commercial Reactors

Date	Plant	Peak Acceleration observed	Design SSE	Description
1986	Perry (US)			The Perry plant in Ohio USA, exceeded its design basis limit while under construction, but was found acceptable for operation before its licence was issued. Start-up was delayed for over 4 months.
7 Dec 1988	Metsamor (Armenia)	5.5 (MSK-64)	MSK 8° ~ 0.2 g	The two units at Metsamor Nuclear Power Plant in Armenia were hit by the Spitak earthquake (1988) with an epicentre 75 km from the power plant. No automatic seismic SCRAM was initiated as signals were lower than the designed trigger level. No safety related or non-safety related system damage resulted. After the earthquake, both units were shut down by government decree, which resulted in complex reconstruction and seismic upgrade programme and additional site seismic hazard studies. It has been subsequently reopened due to power shortages, after redefining its SSE and some modification.
16 August 2005	Onagawa NNP (Japan)	265 gal 0.27 g	375 gal 0.38 g	The three units at the Onagawa plant in Japan exceeded their design basis seismic response spectra over some frequency ranges, due to the 7.2 M _{JMA} Miyagi earthquake 73 km south-west of the site. This resulted in an automatic seismic SCRAM on all three units. No safeguard equipment was affected, and damage on the site was limited to window cracking, road cracking, and some minor waste storage building. The earthquake resulted in the redefinition of the DBE (reactor building basemat) up to 597 gal (1 g = 980 gal).

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Date	Plant	Peak Acceleration observed	Design SSE	Description
25 March 2007	Shika NPP (Japan)	264 gal 0.27 g	332 gal 0.34 g	<p>The two units at Shika plant exceeded their design basis seismic response spectra over some frequency ranges, due to the 6.9 M_{JMA} Noto Hantou earthquake 18 km north of the plant.</p> <p>Both units were shut down at the time, and there was no damage to safeguard equipment, but non-nuclear damage included:</p> <ul style="list-style-type: none"> • Loss of off-site power, • Seismically induced events, • Water spilled (45 t) from spent fuel pool over unit 1, • Mercury vapour lamps fallen down at units 1 and 2, • Displacement of turbine rotors of unit 2 in the process of being assembled, • Rupture discs actuated in transformers, and • Evidence of impact between structural elements in turbine building.
16 July 2007	Kashiwazaki-Kariwa NPP (Japan)	680 gal ~0.7 g	273 gal (0.28 g)	<p>Three units at Kashiwazaki-Kariwa plant in Japan exceeded their SSE design basis significantly, due to the Niigata Chuetsu-Oki earthquake's (6.6 M_w) with an epicentre only 16 km from the site.</p> <p>All plants' control rods inserted successfully and shutdown was successful. Four reactors shut down automatically at the pre-set level of 120 gal; the other three were not operating at the time. Damage was limited to non-safety systems and included:</p> <ul style="list-style-type: none"> • Loss of off-site power, • Fire on a unit 3 transformer, • Internal flooding due to rupture of fire extinguishing pipe, • Loss of service water due to rupture of pipe, and • Damage to the emergency response centre. <p>The in-structure response spectra of the observed recorded significantly exceeded those calculated for the design in almost all the frequency ranges. The plant's seismometers measured PGA of 332 to 680 gal, the OBE (SL1) design bases for different units being 170 to 270 gal and the SSE (SL 2) figure on actual bedrock was 450 gal. The peak ground acceleration thus exceeded the OBE design values on all units, hence the need to shut down, and the SSE values on units 1, 2, and 4. Unit 1 exceeded its design basis by factor of ± 3.</p> <p>This event led to the re-definition of the DBE, as high as 1000 gal for units 6 and 7.</p>

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Date	Plant	Peak Acceleration observed	Design SSE	Description
11 March 2011	Fukushima NPP (Japan)	550 gal 0.56 g (Unit 2)	438 gal 0.45 g (Unit 2)	<p>The magnitude 9.0 Mw Tohoku earthquake resulted in any considerable damage; and created a devastating tsunami, with a run-up height of up to 40 metres. It appears to have been a double quake giving a severe duration of about 3 minutes, centred 130 km offshore of the city of Sendai on the eastern coast of Honshu Island. It moved Honshu 4-metres east and apparently subsided the nearby coastline by half a metre.</p> <p>Eleven reactors at four nuclear power plants in the region were operating at the time and all shut down automatically when the quake hit. Power was available to run the cooling pumps at most of the units, and they achieved cold shutdown in a few days. The operating units that shut down were Fukushima Daiichi 1, 2, 3; Fukushima Daini 1, 2, 3, 4; Tohoku's Onagawa 1, 2, 3; and Tokai. Onogawa 1 briefly suffered a fire in the non-nuclear turbine building, but the main problem centred on Fukushima Daiichi units 1-3.</p> <p>At the Fukushima Daiichi plant, the three reactors were shut down by the earthquake and the emergency diesel generators started as expected, when off-site power was lost. The generator failed an hour later when submerged by the tsunami, which was about 15 metres high locally.</p> <p>The design basis acceleration for both Fukushima plants had been upgraded in 2008, and is now quoted at horizontal 441-489 gal for Daiichi and 415-434 gal for Daini. The interim recorded data for both plants shows that 550 gal (0.56 g) was the maximum for Daiichi, in the foundation of unit 2 (other figures 281-548 gal), and 254 gal was maximum for Daini. Units 2, 3, and 5 exceeded their maximum response acceleration design basis in E-W direction by about 20%.</p>

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Date	Plant	Peak Acceleration observed	Design SSE	Description
23 August 2011	North Anna	0.27 g	0.12 g/ 0.18 g	<p>A magnitude 5.8 earthquake occurred near Mineral, Virginia, close to the North Anna Power Station. The earthquake caused the reactor plants to shut down automatically and resulted in a loss of off-site power. There was minimal earthquake damage, with all safety-related equipment performing as it should, with the possible exception of the coolant leak associated with one of the emergency diesels.</p> <p>The North Anna Power Station has two safe shutdown earthquake ground motions, one for structures, systems, and components located on top of rock, which is anchored at 0.12 g, and the other for structures, systems, and components located on top of soil, which is anchored at 0.18 g. The plant has two corresponding operating basis earthquake ground motion spectra, anchored at 0.06 g for rock and 0.09 g for soil. At several frequencies, the spectral and peak ground accelerations as a result of the earthquake were greater than both the OBE and SSE.</p>

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