Perspective on Seismic Hazard Assessment for Nuclear Reactor Installations in Australia

Prepared by: T V Diamond (ARPANSA)

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1. Introduction.

1. This paper is written from the perspective of the Australian nuclear safety regulatory body, previously the Nuclear Safety Bureau (NSB), and now the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA). ARPANSA is an independent regulatory body established by the *Australian Radiation Protection and Nuclear Safety Act 1998*. The regulator is the CEO of ARPANSA.

2. The operating organisation is responsible for the safety of its nuclear installation including appropriate levels of seismic safety in the design, construction and operation of its nuclear installations. The regulatory role of ARPANSA in seismic safety is an oversight role in the sense that during an assessment of an application for licence, the regulatory body has to be assured that international best practice in nuclear safety has been taken into account, by the operator and its consultants in achieving nuclear safety. This includes a requirement that the operating organisation demonstrates adequate seismic safety margins in nuclear safety related buildings, structures, systems and components.

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3. Australia has no nuclear power plant (NPP), and the only nuclear installations currently in Australia are owned and operated by the Federal Government agency, the Australian Nuclear Science and Technology Organisation (ANSTO). Currently, at its Lucas Heights site in Sydney ANSTO operates the research reactor (OPAL) and some non reactor nuclear installations, all of which have been licensed by the CEO of ARPANSA. Two other research reactors HIFAR and Moata have been shutdown for eventual decommissioning.

4. There is very little specific guidance from codes and standards on the seismic design and construction of nuclear installations other than NPP. In the absence of specific guidance ANSTO, (with ARPANSA's agreement), has used the NPP seismic codes and standards for the seismic design and construction of its new research reactor OPAL. Also as described below NPP codes and standards were used in the refurbishing of the HIFAR research reactor, which

took place in the 1980s and 1990s. The references and standards used are listed and briefly described in Appendix 1.They include international (IAEA) and US national codes and standards for the design of nuclear structures against earthquakes.

5. The paper outlines the development in the approach to seismic design from the 1950s, which generally did not take earthquake loading into account, to the seismic design requirements for OPAL that developed from the extensive seismic and geological studies of the Lucas Heights site and surrounding area in the 1990s. These seismic developments, pre-OPAL are described in Part 2 of this paper, and those that are specific to the OPAL reactor are described in Part 3 of this paper.

6. The CEO of ARPANSA is required under its ARPANSA Act to take into account international best practice (IBP) in nuclear safety and radiation protection when making licensing decisions. This requirement includes seismic safety, and the CEO of ARPANSA informs himself of IBP by ensuring that ARPANSA has a detailed understanding of nuclear safety developments within the International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency (NEA). In addition nuclear power plant countries prone to earthquakes, such as the USA and Japan are monitored by ARPANSA. With this in mind aspects of the recent Japanese major seismic event at Kashiwazaki-Kariwa nuclear power plant site are summarised in Appendix 2 for any lessons learnt.

2. Summary of Seismic Reactor Seismic Design and Analysis at Lucas Heights prior to the OPAL Reactor

1. The predecessor reactor to the OPAL reactor at the Lucas Heights site was HIFAR. The 10 MW research reactor HIFAR was a DIDO type reactor that had been designed by the United Kingdom Atomic Energy Authority (UKAEA) in the 1950s. Six DIDO type reactors were built, three in the UK, and one each in Germany, Denmark and Australia. The HIFAR reactor went critical in 1958 and operated successfully until final shutdown in preparation for decommissioning in January 2007. HIFAR was the last of the DIDO class reactors to be shutdown.

2. At the time HIFAR was designed seismically induced stresses were not taken into account, unless the structure was to be located in an area of known seismic activity. So there was no specific seismic loading considered, but the DIDO designs, and in particular the steel containment structure was very rugged (see Figure 1) since it was designed to withstand the pressures associated with severe accidents.

Figure 1—HIFAR Containment Building.

3. In the early 1970’s a major review of HIFAR safety was undertaken by the Australian Atomic Energy Commission (AAEC) and a HIFAR Safety Document (HSD) was produced. The document concentrated mainly on initiating faults generated from plant related initiating events associated with reactivity insertion accidents (RIA), loss of flow accidents (LOFA) and loss of coolant accidents (LOCA), although some consideration was given to external events such as earthquakes in Sections 2 and 7 of the HSD.

4. The HSD report based its seismic evaluations on studies in the 1960s of the stability of the region that had concluded that the region was seismically inactive. The maximum possible earthquake occurring at Lucas Heights was estimated to have a magnitude of six and an intensity of VII-VIII on the Modified Mercalli Scale. The HSD analysed the capacity of the containment building to withstand ground acceleration. The values chosen were 0.1g horizontal acceleration for the HIFAR design basis earthquake, and 0.2 g horizontal acceleration for the accident earthquake.

5. In the HSD the response of the containment to a 0.2g ground acceleration (peak acceleration of 0.35g) was analysed using the response spectrum method. The period of vibration of the containment was estimated as 0.075 s (13.3 Hz- natural frequency) and a damping of 0.1% was used for the welded steel structure. The estimated stresses and deflections were small and thus the containment was considered to have remained intact in the earthquake event.

The seismic analysis concentrated on the behaviour of the containment, and was silent on any seismic contribution to core damage.

6. For many years following the HSD the safety philosophy adopted for HIFAR, in respect of seismic events, was that the containment should be regarded as the primary defence mechanism against the release of fission products to the environment. However, in the 1980s and 1990s this view changed, when it became clear, through probabilistic safety analyses in Australia and overseas, that earthquake events might represent a greater total public risk from reactor operation than previously had been considered. This led to a seismic reassessment of HIFAR as part of HIFAR refurbishing programme undertaken in 1984. This study identified certain plant weaknesses, which raised doubts on the HIFAR capability to sustain a seismic event giving rise to 0.2g horizontal ground acceleration. Following this time "an intact core philosophy" was adopted for the seismic refurbishing of HIFAR.

7. A seismic hardening program for HIFAR was initiated in the late 1980s, involving some HIFAR structural modifications, and the strengthening and decoupling of the adjacent buildings to HIFAR to eliminate possible effects on HIFAR from the seismic failure of these adjacent buildings. The seismic strengthening was based on a ground acceleration of 0.23g, which was then considered to have a return period of 10,000 years. In addition to its use in the seismic refurbishing of HIFAR structures, the 0.23g horizontal ground acceleration value was used for the refurbishing of the HIFAR engineered safety features, such as the emergency core cooling system, the containment space conditioner system and the standby electrical power supply provisions.

8. In 1997 a major probabilistic safety assessment (PSA Level +1) was undertaken for HIFAR looking at core damage frequency and containment failures. The HIFAR PSA identified seismicity as the major contributor to the core damage frequency (of the order of $1*10^{-4}$ per year or more than half the total contribution to core damage frequency). The team that undertook the PSA (PLG) had experience in undertaking PSAs in low seismicity regions of the USA, and suggested that there were significant uncertainties in the earthquake hazard curves recommended to it by ANSTO. In the HIFAR PSA they had increased the uncertainties in their PSA to take account of the USA information and this had increased the earthquake –initiated fuel damage frequency. They suggested however, that there should be an evaluation of these uncertainties for the seismic conditions in the Lucas Heights region.

9. A key seismic engineering input into the HIFAR earthquake analysis undertaken as part of the HIFAR PSA was the development of the probability of failures (or fragilities) for key HIFAR components. Tables were produced for a whole range of HIFAR structures, systems and components (SSC), both safety related and non safety related. Much of the assignment of fragility was based on the PLG team experience in US NPP walk downs and HIFAR site plant walk downs. They identified mean design earthquake ground acceleration values for the SSC and also uncertainty factors based on US data. This approach permitted them to specify high confidence low probability of failure (HCLPF) ground acceleration values for a large range of SSC. In

addition they identified the failure modes of the SSC, including collapse, pipe break, walking of equipment, or disconnects.

10. Following the recommendation of the authors of the HIFAR PSA the Institute of Geological Nuclear Studies (IGNS) was contracted by the former Department of Industry, Science and Resources (DISR) to perform a probabilistic seismic hazard analysis (PSHA) for the Lucas Heights region. In one of the first probabilistic seismic hazard analyses in Australia, IGNS reviewed the geological setting of the Lucas Heights region to determine the sources of seismicity.

11. In the IGNS study the Lapstone Structural complex was identified as a specific seismogenic source and was assumed to have an 80% chance of being active. A series of five diffuse zones of seismicity was postulated around the Sydney area and based on the seismic record from 1960 through to 1992. The sensitivity studies carried by IGNS indicated that the hazard results were very sensitive to the choice of zonation. The IGNS study also used four attenuation relationships from the USA, each weighted within the logic tree approach adopted to drive the Monte Carlo simulation. Two of these attenuation relationships were from intra-plate regions and two were from inter-plate regions.

12. The results indicated that the mean level horizontal peak ground acceleration for the Lucas Heights site was 0.43g at the 10,000 year return period. This was greater than the 0.23g peak ground acceleration that had been used in the HIFAR PSA. ARPANSA reviewed this IGNS information and commissioned a further study by IGNS to take into account the views of a range of Australian experts. The review indicated that the suggested changes to the depth, maximum magnitude and zonation had little effect on the peak ground acceleration value, but some refinement of the attenuation relationship resulted in a reduction of the acceleration value to 0.37g.

13. In granting a licence to operate HIFAR in June 2001 the CEO of ARPANSA placed a number of seismic related special licence conditions on HIFAR. These included a re-examination of the HIFAR SSC fragility using the IGNS seismic hazard curves and a re-examination of the contribution to core damage frequency using the IGNS seismic hazard curves.

14. In 2003 the HIFAR Safety Document (HSD) was updated to take into account the IGNS information and the ARPANSA comments on the re-examination of seismic contribution to HIFAR core damage frequency. A listing was given of all the seismic category 1 items in HIFAR and the seismic modifications that have been done since 1984. Using the IGNS data and the fragility curves used in the HIFAR PSA the seismic contribution has been estimated to be $1.34*10^{-4}$ per year. HIFAR was finally shutdown in January 2007 following the commissioning of OPAL.

3. Seismic Design and Construction Aspects of the OPAL Reactor

1. The IGNS information discussed above in Part 2 was available at the time of the application to ARPANSA for an application for a facility licence authorising construction of the OPAL reactor. This information had not been available at the time that the CEO of ARPNASA was considering an application for a facility licence authorising ANSTO to prepare a site for the OPAL reactor.

2. Chapter 2 of the safety analysis report (SAR) outlines the seismic classification of structures systems and components as follows:

    a. Seismic Class 1-Items within this class are designed to withstand the consequences of ground motion associated with earthquake level SL-2 (IAEA 50 SG-D15-or the Safe Shutdown Earthquake-SSE).

    b. Seismic Class 2: Items within this class are designed to with stand the consequences of ground motion associated with earthquake level SL-1 (IAEA 50 SG-D15-or the Operating Basis Earthquake (OBE)

    c. Seismic Class 3-Items within this class are designed to withstand the consequences of ground motion associated with normal building and industrial codes (AS 1170 Part1 to 4)—SL-0.

3. A table in Chapter 2 of the OPAL safety analysis report (SAR) gives the classification of systems, subsystems, structures and components including the seismic class. All the Seismic Class 1 and 2 SSC submitted to ARPANSA, as part of the Request for Approval (RFA) to construct process, under the OPAL construction licence. These SSC were designed to remain in the elastic range for the seismic load corresponding to them (131 such RFA submissions were reviewed and approved by ARPANSA). The remaining Seismic Class 3 SSC were designed to AS 1170-Pt 4 and could take credit for ductility beyond the elastic behaviour (see Appendix 1).

4. The design basis ground motions used for the three seismic levels adopted for the facility are:

    - Sl-2 Peak ground horizontal acceleration:-0.37g and a peak vertical acceleration of 0.25g. The acceleration response spectrum shape is taken as envelope between the IGNS spectrum scaled to 0.37g and the USNRC Regulatory Guide 1.60 scaled to 0.3 g. This envelope maximises the acceleration over the whole frequency range.

- SL-1-Peak ground horizontal acceleration of 0.09g and peak vertical ground acceleration of 0.06g. The acceleration response is taken from US NRC Regulatory Guide 1.60 scaled to the peak ground acceleration.

- SL-0 -This level corresponds to the earthquake loads for civil structures. It is specified in accordance with AS1170.4 Minimum design loads on structures Part 4-Earthquake Loads

5. The Time History Analysis Method was used in Seismic Category 1 and 2 structures in order to generate the OPAL reactor floor response spectra. These spectra have been taken as dynamic inputs to design the equipment and components at all the floor levels and was clearly identified in the safety related RFAs for construction submitted to ARPANSA for approval. More information design codes, modelling etc is presented in Appendix 1 to this paper. Figure 2 below shows seismic piping supports used in OPAL for the primary cooling system piping, and the separation of the pumps into differing quadrants.

Figure 2 --OPAL Seismic Supports for Primary Circuit Piping

6. ARPANSA retained an international seismic structural expert to review the seismic and aircraft impact general design of reactor buildings and structures submitted as part of the Construction Submission. In the consultant's report the following general observations and conclusions were made:

   - The seismic analysis and design procedures used for the replacement research reactor (OPAL) met the international standards for nuclear power facilities, including nuclear power plant.

   - Implementation of the design and construction programs, as described in the SAR, will lead to facility with a high level of seismic capacity, including beyond design basis capacity.

   - The seismic design ground motion, defined by the envelope of the 0.3g US NRC Regulatory Guide 1.60 response spectra with the IGNS 0.37 site specific response spectra, is extremely conservative with respect to spectral shape.

   - The "push over" analysis to determine the level of equivalent lateral load that causes extensive shear wall and diaphragm damage is not predicted prior to about two times the SL-2 acceleration value.

   - Seismic walk downs should be performed at various stages during construction to identify potential failure modes and in order to establish the final fragility values for components to be used in the "as built" seismic PSA. Areas highlighted were flooding or water spray associated with failure of non seismic category 1 systems such as fire protection piping, as well as seismic induced fires lube oil leaks on hot piping (see Appendix 2 for some related comments on the recent Japanese KK earthquake induced damage).

7. ARPANSA commissioned an IAEA Peer Review to review the seismic and other construction aspects submitted with the application for a facility licence authorising ANSTO to construct OPAL. The IAEA recommended that an additional seismic study be undertaken for the Lucas Heights in accordance with the recommendations of the IAEA Safety Guide 50-SG-S1. ARPANSA required ANSTO to undertake such a task and a paleo-seismologist evaluated the site for evidence of recent faults out to 5km radius from the reactor. The examination undertaken found no evidence of any active faults.

8. Following the commencement of reactor facility excavations in July 2002, the detailed geological mapping of the replacement research reactor site, led to the identification and subsequent ageing analysis of the two main fault strands found. Reactor construction was held up for four months until the geological and seismic investigations of the capability of the fault were

completed and ARPANSA informed of the outcome. This was an extensive examination and Appendix 1 describes the key investigation papers and outcomes.

9. The faults found strike to the north-north east dip steeply (mostly 65-80 degree east and west), and have dip separations of 1 to 1.3 m (the eastern strand and 0.2 to 0.3m (the western strand). In net displacement terms, the eastern fault strand was an apparent normal fault and was the dominant fault trace observed extending for at least 140m across the construction site. The western fault strand was the second largest observed and had apparent reverse displacement, this fault extended 120 m across the site and converged in the northern part of the construction site to form a single fault zone. Following detailed assessment (see papers in Appendix 1) the last movement of the western fault (reverse fault) was determined as being at least 5-13 million years ago. This was consistent with the thermo-chronology results of 10 to 35 million years, and the faults were possibly as old as the Tasman Sea opening of 53-83 million years. (See Figures 3 and 4 below for photos of the two fault strands described above).

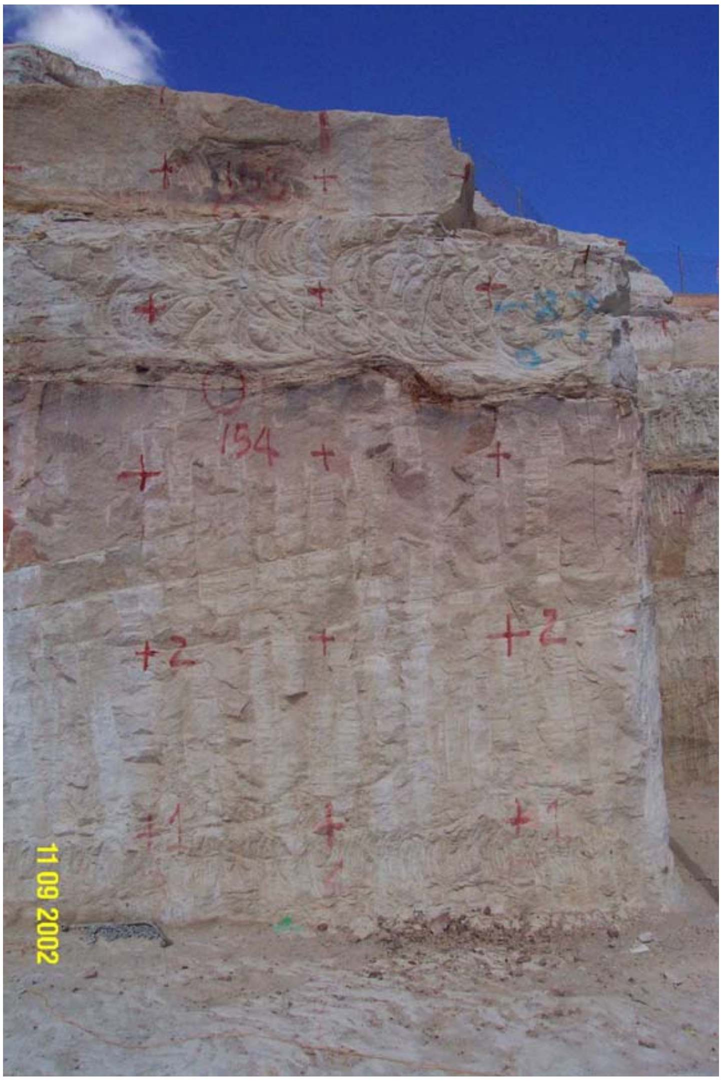

Figure 3 Western Fault-South Wall

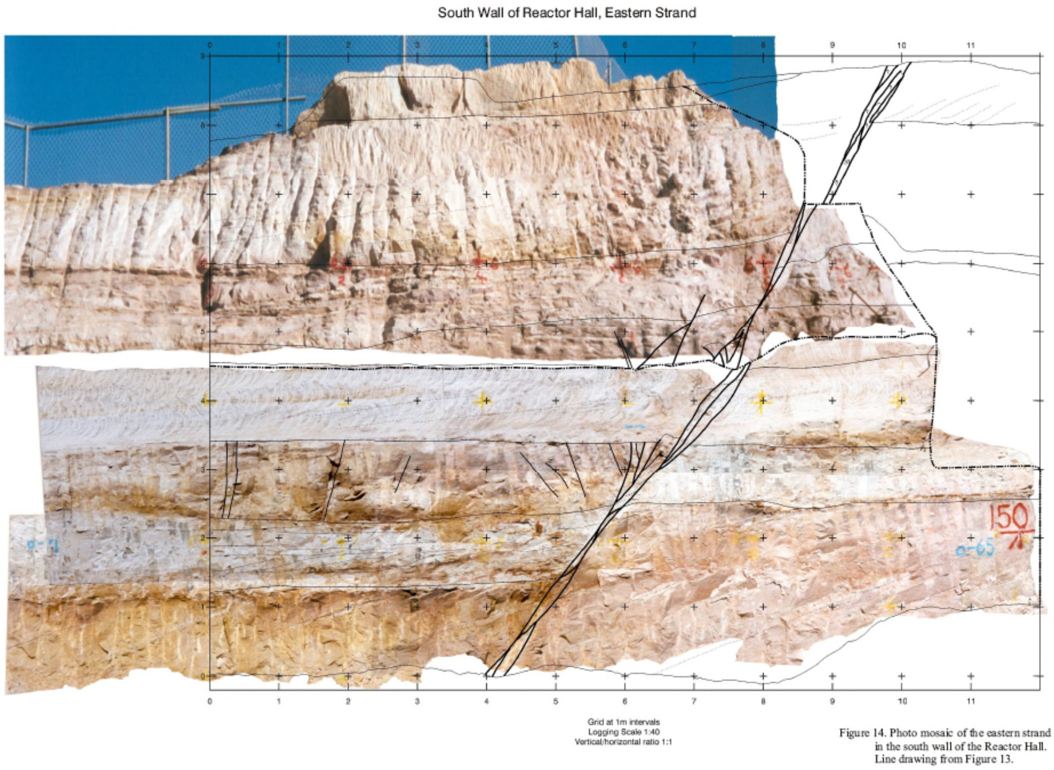

Figure 4 -Eastern Strand-South Wall

10. Details of the ANSTO sponsored investigations and ARPANSA independent regulatory seismic safety assessments are summarised in Appendix 1. The assessment by the CEO of ARPANSA-of the site geological investigations for the Replacement Research Reactor (now known as OPAL) at Lucas Heights was given in October 2002. The CEO concluded that, based on the advice and evidence submitted, the faulting on the site of the OPAL reactor is not capable of resulting in surface displacement and that the seismic design of the RRR (now OPAL) remained valid.

11. The ARPANSA assessment of the proposed design and construction of OPAL continued following the ARPANSA CEO decision, and did not take into account the possibility of subsurface faulting at the OPAL site. The seismic design basis approved in the facility licence for the OPAL reactor was used for structures, systems and component (SSC) of the OPAL reactor. In the case of safety related SSC the detailed design analyses were available for ARPANSA review through the Request for Approval process for each safety related SSC prior to construction. The detailed design submissions clearly identified the safety class, the seismic category and quality requirements. A typical example of the types of supports and anchors used is shown in Figure 2.

12. ANSTO received an Operating Licence for the OPAL reactor from the CEO of ARPANSA in July 2006.

4. Conclusions

1. The paper outlines the development in the approach to seismic design from the 1950s, which generally did not take earthquake loading into account, to the seismic design requirements for OPAL that developed from the extensive seismic and geological studies of the Lucas Heights site and surrounding area in the 1990s. These seismic developments, pre-OPAL are described in Part 2 of this paper, and those that are specific to the OPAL reactor are described in Part 3 of this paper.

2. There is very little specific guidance from codes and standards on the seismic design and construction of nuclear installations other than those for nuclear power plant (NPP). In the absence of specific guidance ANSTO, (with ARPANSA's agreement), used the NPP seismic codes and standards for the seismic design and construction of its new research reactor OPAL. Also the NPP codes and standards were used in the refurbishing of the HIFAR research reactor, which took place in the 1980s and 1990s.

3. ARPANSA is a small nuclear regulatory agency and does not have seismologists, geologists on its regulatory staff. In order to get advice in safety matters relating to earthquakes it was necessary for the CEO of ARPANSA to seek external advice. Specialist consultants, from within Australia and overseas, were used to review and advise on a range of matters that emerged during the siting, construction of the OPAL reactor. The approach was to interface the consultant's views into the ARPANSA regulatory assessments. It worked very successfully and included three missions by experts suggested by the International Atomic Energy Commission (IAEA).

Acknowledgement

The views expressed in this paper are those of the author and do not necessarily reflect those of ARPANSA. I would also like to thank ANSTO for their permission to use some HIFAR and OPAL reactor photos in this paper.

Appendix 1

Seismic Nuclear Codes, Standards, Guidance Documents and Computer Models, used for the ANSTO OPAL Reactor. The List covers Design and Construction as well as the ARPANSA Regulatory Assessments.

1. The Consolidated Report—Methods, Criteria, and Analysis for Seismic qualification (RRRP-7500-EBEAN-001 A-November 2001) included clarification as to the use of appropriate codes and standards, as well as conservatively selected loading combinations. The report was part of seismic design approved by ARPANSA CEO for the construction of the OPAL reactor in April 2002.

2. The ARPANSA Regulatory Assessment Principles (ARPANSA 2001) do not set down any seismic standards. However, seismicity is recognised as an important potential accident initiator with the possibility of causing common cause failure of safety systems and impairment of several layers of defence in depth. A number of Regulatory Principles and Design Criteria are relevant and are briefly summarised below:

    - Principle 20 (i) requires the safety analyses to consider internal and external hazards including earthquake.

    - Principle 54 requires that the design of a facility takes into account site characteristics, which may impact on the safety of the facility, and this includes the site's seismology.

    - Principle 37 states that probabilistic methods may be used to confirm that the design of safety systems is suitably fault tolerant and balanced (no single accident dominates). It also requires that the design and safety analysis demonstrate adequate protection against design basis accidents. In addition for the beyond design basis accidents there should be no "cliff edge "effect, that is, a sudden increase in consequences at the lower frequency accidents.

    - Design Guideline Criterion 77 calls for a program of design verification that addresses environmental and seismic testing to demonstrate the capability of SSC that are important to safety.

    - Design Guideline Criteria 105, 108, and 264 require analysis of the design of the containment and confinement systems to address seismicity.

- In the case of reactors Design Guideline Criterion 162 requires the design and design basis analysis to address severe earthquakes having a mean return period up to 10,000 years.

- Design Criterion 247 requires the design of the emergency or standby power supply to address the various load groups and the need for redundant sub systems, to take into account the design basis seismic events.

3. In accordance with the ARPANSA Regulatory Assessment Principle and Design Guidance the OPAL Safety Analysis Report (Chapter 2) outlines the seismic classification of SSC as follows:

   - Seismic Class 1-Items within this class are designed to withstand the consequences of ground motion associated with earthquake level SL-2(IAEA 50 SG-D15)-or Safe Shutdown Earthquake).

   - Seismic Class 2: Items within this class are designed to with stand the consequences of ground motion associated with earthquake level SL-1 (IAEA 50 SG-D15)-or Operating Basis Earthquake (OBE)

   - Seismic Class 3-Items within this class are designed to withstand the consequences of ground motion associated with normal building and industrial codes (AS 1170 Part1 to 4)—SL-0.

4. The methodology for seismic definitions and qualification for OPAL has been adopted in accordance with guidance from the IAEA and the US Nuclear Regulatory Commission Seismic Regulatory Guides. However, there is some credit taken for the one non NPP document listed below in relation to anchorages and piping supports. The documents are:

   - IAEA Safety series 50-SG-S1-Earthquake and associated topics in relation to nuclear power plant (NPP) siting.

   - IAEA Safety Series 50-SG-D15-Seismic design and qualification for nuclear power plants.

   - USNRC Regulatory Guide 1.61-Damping values for seismic design of nuclear power plants.

   - USNRC Regulatory Guide 1.92-Combining modal responses and spatial components in seismic response analysis.

   - US NRC Regulatory Guide 1.122-Development of floor response spectra for seismic design of floor supported equipment or components.

- IAEA TECDOC -348 -Earthquake resistant design of nuclear facilities with limited radioactive inventory.

5. For the concrete and steel design of Seismic Categories 1 and 2 the American Concrete Institute Building codes were used for estimating the load combinations. In addition aspects of Australian Standards are used for seismic category 1, 2 and structures. The relevant codes and standards are:

    - American Concrete Institute Building Code Requirement for structural concrete for Seismic Class1 and 2 structures. (ACI-318-1995).

    - Code Requirements for nuclear safety related concrete structures for load combinations of Seismic Class 1 and 2 (ACI 349-1997).

    - IAEA Safety Guide 50-SG-D-15 for seismic cycles and structural ductility. Noting the intent for both the Safe Shutdown (SSE) and Operating Basis (OBE) earthquakes to keep the stresses in the elastic range.

    - American Society of Civil Engineers—ASCE 4-98 " Seismic Analysis of safety Related Nuclear Structures and Commentary" was used to determine the ground motion damping values for the SSE and OBE (with 7% for SSE and 4% for OBE).

    - AS 1170 Pt 1-4 Australian Standard Loading Code for Seismic Category 1, 2, and 3 structures. The loading criteria however follow the NPP standards and are well in excess of AS 1170-Pt 4.

    - AS-3600-Australian Standard Concrete Structures used Seismic Class 1,2, and 3 structures

    - AS4100-Australian Standard Steel Structures Code used for Seismic Category 1, 2 and 3 structures.

6. In terms of modelling the reactor building structures for seismic loads the modelling takes into account:

    - 3 D modelling of the reactor building Concrete Elements using the Computer Code SAP 2000NL with a range of finite element blocks including plate, shell and brick elements.

    - Seismic mass of the building using the approach recommended in IAEA TECDOC -348.

- The rock structure interaction was conservatively modelled as being supported on the rock foundation without lateral support from adjacent soil or rock. Based on measured values by Coffey Geotechnical Services, done as part of the Site Environmental Impact Statement (1998) EIS, the recommended design value for the rock vertical stiffness was 480 kPa mm^{-1}.

7. The analysis of the reactor building structures included the response spectrum method for the SSE and OBE and included the first 20 natural modes of vibration in order to ensure not less than 90% of the mass had participated in the direction under consideration. In addition the elastic time history method was used to provide the floor response spectra at the various levels of the reactor building as input to the seismic design of equipment at the various levels. Three statistically independent sets of ground motion time histories were developed synthetically using the OBE and SSE design spectra (Figure 4.4/15 of the OPAL Safety Analysis Report).

8. The detail design computer codes used were:

   - In the preliminary design phases ETABS& was used for equivalent static and response spectrum seismic analysis of the concrete framing to evaluate earthquake induced member design actions and input forces for foundation analyses.

   - SAP2000NL was used for the detail design phase and 3D response analyses were undertaken to evaluate earthquake induced internal forces for member design, lateral story displacement, storey shears, and storey over turning moments etc.

   - Independent verification of the design by the computer codes ABAQUS and NISAII, particularly where non linear analyses were done in the event of concrete cracking models.

   - The aircraft impact grillage was modelled using the finite element analysis program STRAND7; particularly where non linear stress strain relationships for the material properties or plate elements were required.

   - For the safety related seismic category 1 and 2 reactor structures, systems and components (SSC) mounted at the various floor levels the finite element analyses used the MSC/NASTRAN code.

9. There were many review papers associated with the site geological investigations following the discovery of faults during the OPAL site excavations. The faults were found following the decision by the CEO of ARPANSA to issue a facility licence to ANSTO authorising construction of the OPAL reactor. The main papers were:

- Submission to ARPANSA on the Site Geological Investigations for the Replacement Research Reactor at Lucas Heights (RRP-7500-3BEAN-002-A. This paper gave all the details of the fault strands found during excavation and the ANSTO sponsored investigations undertaken. It also gave arguments to support that the faults were not capable based on comparison with guidance from the IAEA and US NRC.

- Additional Geological Investigations undertaken in Support of the Replacement Research Reactor at Lucas Heights (RRRP-7500-3BEAN-003-A).This report draws together, and provides an overview of reports on a range of additional ANSTO sponsored investigations undertaken as part of a geological assessment of the RRR (now OPAL) site following the discovery of faulting on the site. These investigations included site assessments, fault dating methodologies, studies of the regional geology and peer reviews.

- ANSTO-Replacement Research Reactor Project Task 3-Probabilistic Fault Recurrence Evaluation (IGNS-2002). The study was undertaken as a probabilistic analysis to determine the likely range of mean recurrence intervals for surface rupture of the RRR site fault. The approach taken used the knowledge of the size of the reverse displacements on the western fault strand, combined with scaling properties and other geological information, to estimate likely average sub surface single event displacements (SED's). The results indicated that the mean recurrence interval of surface rupturing earthquake was 13.13 million years.

- ARPANSA sponsored IAEA report on "Review of the Assessment of Surface Faulting at the RRR Site at Lucas Heights, Australia (September 2002). The report was prepared by Mr Leonello Serva (Italy) and was based on his own investigations as well as review of the above ANSTO submissions. The review concluded that the last tectonic movement that occurred at the fault at RRR foundations is extremely old. As a minimum and in the most conservative case the fault is older than 5 million years, and therefore according to the IAEA criteria, it is not considered a capable fault.

- ARPANSA Report RB-ASR-48-02 Review of the ANSTO Submission on the Site Geological Investigations for the RRR at Lucas Heights. This report summarised all the available information on the site geological investigations, as well as the seismic design of OPAL that had been submitted as part of the Construction Licence Application. The report concluded that the faults discovered during the RRR site investigations were not capable, within the IAEA or USNRC definitions, of causing surface displacement. The fault was not active and unlikely to re-activate within the lifespan of the RRR. The report recommendation was that the RRR need not be designed for surface displacement, and that the discovery of the faulting does not impact on the IGNS results from which the RRR (OPAL) seismic design and construction was derived.

- IAEA Safety Guide 50 SG-S1-1979-Earthquakes and Associated Topics in Relation to Nuclear Power Plant Siting. The key element with respect to surface faulting is Criterion 1" *A fault shall be considered capable if it shows evidence of past movement of a recurring nature within such a period that is reasonable to infer that further movement at or near the surface can occur. In less active areas it is likely that much longer (than order of tens of thousands of years) may be required"*.

- US Nuclear Regulatory Commission, Regulatory Guide 1.165. Fault Capability Criteria (see also US 10 CFR Pt 100-App A- Seismic and Geological Siting Criteria for Nuclear Power Plants). In the NRC criterion the timescale is defined as "*of a recurring nature within the last .approximately 50,000 years, or at least once in the last, approximately, 50,000 years"*.

- Assessment by the CEO of ARPANSA-site Geological Investigations for the Replacement Research Reactor at Lucas Heights (October 2002).

10. Based on the above advice and evidence the CEO found that the faulting on the site of the RRR (now OPAL) was not capable of resulting in surface displacement and that the seismic design of the RRR remained valid.

Appendix 2: Preliminary Findings from the 16 July 2007 Earthquake at Kashiwazaki-Kariwa NPP

1. The KK nuclear power plant (NPP) site is the biggest nuclear power plant site in the world with seven units and a total of 7965 MW net installed capacity. The reactors are operated by Tokyo Electric Power Company (TEPCO) with five reactors of the Boiling Water Reactor (BWR) type (Units 1 to 5), and two of the Advanced Boiling Water Reactor (ABWR) type (Units 6 and 7).

2. At the time of the earthquake Units 2, 3, 4 and 7 were in operation and Unit 2 was in the startup condition, with the other Units shutdown for planned outages. The strong Niigataken Chuetsu-Oki earthquake affected the KK site at 10-13 hours local time on the 16 July 2007. The earthquake moment magnitude was 6.6, with its epicentre about 16 km north of the KK site. Measurements on the KK site using the installed site accelerometers show, that at the base mat elevation, there was a significant exceedance of the site design basis acceleration levels over a very wide range of spectral frequencies. One of the measurements indicated that the surface of the site near a switchyard had peak ground accelerations approaching 1g.

3. The reactor safety related structures, systems and components (SSC) worked as designed. All of the operating reactors were shutdown safely by the insertion of control rods triggered by dedicated seismic trips

4. The decay heat removal was effective and the operators maintained the necessary heat sinks in operation after shutdown (second level of defence in depth). The containment function was maintained, although a minor airborne release was later measured, but was shown to be associated with human error and not with the earthquake event.

5. There was no loss of offsite power, which normally would be assumed in earthquakes of this magnitude involving ground acceleration in excess of 0.25g. This was a surprising outcome and may have some impact on future seismic safety assessments to take into account sit specific factors for off site power provision.

6. Some low grade contaminated water was inadvertently pumped out to sea. The water was from spillage that occurred due to sloshing of a spent fuel store pool that leaked into the discharge pit. In addition barrels of solid radioactive waste in a store toppled but did not release their contents.

7. The management of the event in all units was successfully carried out with respect to the operation of the reactor safety systems. There was however an eight hour delay in informing the authorities and other agencies involved in emergency response of the contaminated water leakage to sea.

8. A number of failures of non safety related SSC, but there were no systems interactions with the safety related SSC due to proximity or collapse of structures and components. Many of the problems at the KK site were induced by large soil deformations. Investigations by TEPCO and an IAEA team indicate that some of the failures could be associated with the initial selection of material for back filling and compaction, and lack of flexibility or expansion joints that would permit large displacements. The IAEA review team also suggested that ground water may have been a contributed to the soil liquefaction and large soil deformations. They suggested that actions should be taken to lower the ground water level or to pump it out.

9. The main failures of the non safety related SSC were:

    a. Unit 3 experienced a fire in an in house transformer caused by anchorage failure that resulted in a cable short circuit and transformer oil spillage that was ignited by the sparks. This fire was put out after 2 hours by the local fire brigade due to the failure of the on site fire system.

    b. A safety significant failure was the common cause failure of the site fire piping system. The failures occurred in a number of separate locations and were due significant soil deformation that caused failures of piping, tanks, pumps, and distribution (including embedded piping).

    c. Another common cause failure was to inlet ducts to a number of stacks due to settlement and soil failure in structures and components interconnected

    d. A number of fluorescent light fixtures fell down in the control rooms but did no damage to people or equipment.

10. There were a limited number of anchorage failures mainly on transformers and water tanks that are not safety related. The IAEA review team raised the importance of walk downs and a proper ageing management system to maintain the anchorages healthy and avoid weakening from corrosion or vibration. However, in general the extensive use of strong anchorages on non safety related SSC prevented falling or proximity hazards from occurring during the earthquake.

11. The measured seismic and damage information collected at the KK site should be very useful for future seismic assessments. Site specific factors such as the retention of off site power could be factored in some cases and reduce the core damage frequency in seismic events.

12. A particular issue of concern was the common cause failure of the fire fighting systems on the KK site. While not a safety related SSC, the system is nevertheless very important. Such fire systems with its pipes, pumps, tanks and distribution fire fighting systems need to consider improved design of anchorages, and some redundancy and possibly diversity.

13. The owner of the reactors Tokyo Electric Power Company (TEPCO) has begun in core inspections of the reactors. This requires the removal of fuel assemblies and control rods. In the case of one reactor (unit 7) all 205 of the 4 metre long control rods have to be removed. To date 106 have been removed, but one remains jammed in the core. The cause is not yet known. All seven reactors at the plant remain offline while damage from the earthquake is assessed.