SEISMIC PSA OF KERNKRAFTWERK NECKARWESTHEIM UNIT 2 (GKN II)

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ABSTRACT

German nuclear regulations require that nuclear power plants with a design basis earthquake greater than Intensity 7 perform a seismic probabilistic safety assessment (PSA). Based on the existing seismological investigations, the GKN site falls into this category; therefore, a seismic PSA was conducted on GKN II as described in this paper. The assessment considered both system damage state frequency (SDSF – the condition of a threat existing to the core before any accident management actions are performed) and core damage frequency (CDF – the condition of damage to the core after all attempts to perform accident management have been considered). This paper focuses on the seismic fragility aspect of the seismic PSA, including seismic walkdown review, screening of components, and seismic fragility calculations of non-screened structures and equipment.

The study has demonstrated that, given the high seismic design capacity of the GKN II SSCs, seismic events do not constitute a credible challenge to the plant. The detailed seismic walkdown and review of design documents for fragility evaluation have further enhanced the seismic safety of the plant. In the walkdown, seismic spatial interaction issues and housekeeping items were identified. With these issues resolved, GKNII has achieved increased safety against seismic hazards.

INTRODUCTION

German nuclear regulations require that plants with MSK Intensity greater than 7 perform a seismic PSA. On the basis of existing seismological investigations the GKN site falls into this category; therefore, a seismic PSA was conducted on GKN II as described in the present paper. While the seismic hazard analysis is a necessary part of the seismic PSA, it was treated in this study as an input. A probabilistic seismic hazard analysis was conducted for GKN under a separate project and the results provided for use in the seismic PSA.

The present study is aimed to be consistent with the international practices that form the current state-of-the-art, and with the specifications as outlined by the German PSA Guidelines [1]. The seismic PSA was performed in accordance with the requirements for Capability Category II in ANSI/ANS 58.21-2007 Standard [2]. The Standard requires that a detailed walkdown be conducted for the purposes of identifying seismic vulnerabilities and for screening those structures, systems, and components (SSCs) that are inherently rugged and would have insignificant contribution to seismic core damage frequency. Detailed requirements on walkdown procedures and documentation given in EPRI-NP 6041 [3] were followed in conducting the walkdown. Seismic fragilities were developed for SSCs that were not screened by following the guidance given in EPRI TR-103959 [4].

METHODOLOGY AND PROCEDURES

The key elements of a seismic PSA are:

- **Seismic Hazard Analysis:** to develop frequencies of occurrence of different levels of ground motion at the site. Note that the seismic hazard analysis for GKN II site was conducted in a separate project, and the results were provided for the SPSA project.
- **Seismic Equipment List (SEL):** to develop a list of SSCs whose seismic-induced failure could prevent safe shutdown of the plant and lead to core damage.
- **Systems/Accident Sequence Analysis:** to model the various combinations of structural and equipment failures, as well as human errors that could initiate and propagate a seismic core damage sequence.

- **Seismic Walkdown Review and Screening:** to screen out seismically rugged equipment from detailed fragility evaluations, to define failure modes of equipment that is not screened, to identify seismic interaction concerns, and to address issues of seismic-induced fire and seismic-induced flooding.
- **Seismic Fragility Evaluation:** to estimate the conditional probability of failure of screened-in structures and equipment whose failure may contribute to the frequency of core damage.
- **Quantification of CDF:** assembly of the results of the seismic hazard, fragility, and systems analyses to estimate the frequencies of core damage.
- **Documentation and Peer Review:** document the procedures, input data, walkdown findings, fragility estimates and results of quantification of CDF. As part of the documentation, an independent peer review is required.

This paper focuses on the seismic walkdown review and screening of components and seismic fragility evaluations tasks of the GKN II seismic PSA.

SEISMIC DESIGN AND QUALIFICATION CRITERIA OF GKN II

The GKN II nuclear power plant consists of one KONVOI pressurized water reactor unit supplied by Siemens-KWU. The seismic Category I buildings were designed against external loads such as Operating Basis Earthquake (AEB or OBE), Safe Shutdown Earthquake (SEB or SSE), and burst pressure (BDW). The Safe Shutdown Earthquake is defined by the 5% damped United States Nuclear Regulatory Commission (USNRC) Regulatory Guide 1.60 shape anchored to 0.17g peak ground acceleration (PGA) with slight modification to enrich energy contents in the low frequency range. The major plant structures pertaining to the GKN II seismic PSA are: Reactor Containment and Reactor Building Secondary Confinement (UJA/UJB), Main Steam and Feedwater Valve Compartment (UJE), Auxiliary Building (UKA), Switchgear Building (UBA), Emergency Feedwater Building (ULB), Turbine Building (UMA), Emergency Diesel Generator Building (UBP), Service Water Cooling Tower Structure (URB), Service Water Pump Structure (URE), and Vent Stack (UKH).

The Reactor Building (UJA/UJB) and the Emergency Feedwater Building (ULB) were also designed against explosion and aircraft impact. The UBP and the ULB were designed to the enveloping loads of all the potential KONVOI DWR 1300 MW sites in Germany. The KONVOI design floor response spectra of these buildings were observed to be two to three times the GKN II specific design floor response spectra. Thus, there is a significant margin for structures and equipment qualified to the KONVOI enveloping seismic loads.

The GKN II Class I equipment was seismically qualified following the KTA Safety Standards (e.g., KTA 2201.3 and 2201.4 for mechanical and electrical equipment). The design seismic loads are combined with normal operating loads or accident loads. In general, passive equipment (e.g., tanks and heat exchangers) was seismically qualified by analysis, and active equipment (e.g., electrical equipment) was qualified by seismic testing. Single-axis or bi-axial sine sweep tests were used for seismic qualification tests. The amplitude of the sine sweep was conservatively high, such that the equivalent broad-band input motion well enveloped the SEB floor response spectra. Seismic qualification documents of all the SSCs credited in the GKN II seismic PSA were made available for screening and fragility evaluations.

SEISMIC WALKDOWN REVIEW

The procedures used for the seismic walkdown have been developed based on earthquake experience database, seismic qualification test database, and past seismic PSA of nuclear power plants. This methodology has been used in the United States, Canada, Europe, and many other countries in the world to screen out seismically rugged equipment and to direct the resources to components that are more vulnerable to earthquake loadings.

The objectives of the seismic walkdown are to: (1) screen the seismically rugged equipment items; (2) define failure modes (e.g., functionality, structural integrity, or anchorage failure) of the SEL items that are not screened and identify further evaluations required; (3) identify equipment or structures that are not included in the SEL, but whose structural failure may impact the nearby SEL items (i.e., seismic interaction concerns); and (4) address issues of seismic-induced fire and seismic-induced flooding.

Some of the relatively significant observations from the seismic walkdown review are:

- GKN II is well designed and constructed, such that very few seismic spatial interaction issues could be identified.
- Most of the electrical equipment is well-constructed and well-anchored. Adjacent cabinets that are in

close proximity were bolted together to prevent seismic-induced pounding.

- The actuators' height and weight of valves are typically within the screening limits identified in EPRI NP-6041-SL [3]. System interaction concerns, associated with proximity to structural elements, were identified for a few valves. Most of these issues can be resolved with minor hardware modifications.
- The main feedwater tank up high in the Turbine Building was judged to have low seismic capacity. Seismic failure of the tank would fail supply of the feedwater system.
- Most of the distribution systems such as piping, cable trays, and HVAC ducts were found to be well supported for gravity load as well as for seismic loads. No vulnerabilities due to seismic-induced anchor movement or differential displacements were observed for the distribution systems.

SCREENING OF SSCs

EPRI NP-6041-SL [3] provides two screening levels for the purpose of a seismic margin assessment (i.e., 0.8g and 1.2g peak ground spectral acceleration at 5% of critical damping). The corresponding PGA are 0.3g and 0.5g, respectively. The generic seismic fragility for components screened at these screening levels was estimated as below:

- Select a HCLPF (High Confidence Low Probability of Failure) capacity and use a generic composite logarithmic standard deviation, β_c, of 0.4 to develop the median capacity. These parameters define a mean fragility curve.
- Convolve the mean site seismic hazard curve with the mean fragility curve.
- For HCLPF capacity in the range of 0.25g to 0.35g PGA, the mean annual probability of failure is given below:

HCLPF PGA Capacity	Annual Probability of Failure
0.25g	9.9E-09
0.30g	1.8E-09
0.35g	3.7E-10

Based on the above-calculated probabilities of failure, the 0.3g PGA was selected as a reasonable screening level for the GKN II SEL components. For building structures, a screening level of 0.5g PGA was selected in consideration of significant consequence of structural failure to the systems and equipment housed in these buildings.

GKN-II design documents such as design sheets, equipment design criteria, vendor drawings, qualification analysis reports or test reports, and anchorage drawings and design reports were reviewed to address issues raised during the walkdown (e.g., masonry walls near electrical equipment, questionable anchorage, etc.). This review resulted in additional screening of SEL items. Because of conservatism in the seismic design of GKN II, more than 85% of the SEL items were screened at 0.3g PGA.

SEISMIC FRAGILITY EVALUATIONS

The methodology for evaluating seismic fragilities of structures and equipment is called Safety Factor method, also known as Separation of Variables method, as described in [4] and [5]. Seismic fragility of structures and equipment at GKN II are presented in terms of the median acceleration capacity, A_m, and the logarithmic standard deviations, β_R and β_U, for randomness and uncertainty. These quantities were calculated using design and qualification analysis and test data; the safety factors reflecting the conservatism or un-conservatism in variables affecting capacity and seismic responses (e.g., strength, inelastic energy absorption, damping, spectral shape, etc.) were evaluated. Seismic fragilities were developed for all structures and equipment that are screened-in and included in the systems models. In the development of seismic fragilities of structures and equipment of GKN II, the above methodology was applied as follows:

- The median capacity, randomness variability, and uncertainty in median capacity are expressed in terms of PGA.
- The existing configuration, as confirmed by review and walkdown, was used in the calculations. When component-specific qualification test and material test data were available, they were used to make the fragility calculations as realistic as feasible.
- Development of seismic fragilities was in compliance with the technical requirements for Capability Category II given in the ANS External Event PRA Methodology Standard [2].

Elements of Factors of Safety

The general form of the Factor of Safety is:

$$A = F.\,A_{SSE} \tag{1}$$

where A_{SSE} is a design ground motion parameter, e.g., PGA of the SSE; A is the ground acceleration capacity, and F represents the conservatism or factors of safety in the capacity and the response of the SSCs of interest. F can be further represented as

$$F = F_C * F_{RS} * F_{RE} \tag{2}$$

where F_C is the capacity factor, F_{RS} is the structure response factor, and F_{RE} is the equipment response factor. The median factor of safety, F_m, is related to the median ground acceleration capacity, A_m, as

$$F_m = A_m / A_{SSE} \tag{3}$$

The logarithmic standard deviation of F are then identical to those for the ground acceleration capacity, A. The logarithmic standard deviations, β, are further divided into a randomness, β_R, and uncertainty, β_U, or treated as a composite variability, β_c.

Structure Response Factor

Fragilities of SSCs are dependent on best estimate seismic response of the structures where the SSCs are housed. The structural response defines the seismic input to the SSCs. Hence, a structure response factor of safety, F_{RS}, is needed to estimate median seismic response from the SSE calculated structural response. The structure response factor of safety can be further expressed as product of several factors, such as spectral shape factor, ground motion time history factor, soil-structure interaction (SSI) factor, ground motion incoherency factor, damping factor, structure modeling factor, modal combination factor, and earthquake component combination factor. Each factor represents conservatism and variability of structural modeling or response analysis. Among these factors, the more significant ones in the GKN II seismic fragility evaluations are presented below.

The spectral shape factor of safety represents the relationship between the SSE design response spectral shape and the 1E-5 median site-specific response spectral shape of GKN II. The spectral shape factor was developed from the two spectra normalized to the same PGA value, i.e., A_{SSE}. Depending on the frequencies of the structure dominant modes, this factor of safety varies from 1.1 to 1.3.

The SSI factor of safety represents the relationship between median-centered (or best-estimate) SSI modeling and modeling used in the SSE design analysis. For the GKN II structures, the control point location for the seismic design analyses was defined at the foundation level of each structure, thus ignoring spatial variation of ground motion (i.e., kinematic interaction) in the soil/rock. This is conservative when the ground motion is developed for the surface of the soil/rock at grade. This factor of safety was estimated to be in the range of 1.15 to 1.35 depending on embedment depth and foundation footprint of the GKN II structures.

The damping factor of safety represents the ratio of response between best estimate damping and the design damping value. Two sets of damping factors of safety were calculated. For input to subsystems, building damping factor no higher than 7% of critical damping was considered to be median-centered. The damping factor of safety was determined to be unity. For structure fragility calculations, a damping value of 10% of critical was appropriate, and the factor of safety was estimated to vary from 1.0 to 1.2.

For structure fragility functions, the F_{RS} factor was multiplied by F_C, structure capacity factor to calculate the overall factor of safety, F. As presented in the example below, the structure capacity factor is a product of a strength factor of safety that accounts for conservatism in the code capacity versus the median capacity and an inelastic energy absorption factor of safety that accounts for additional seismic capacity when structure is stressed beyond yield.

Building Seismic Fragilities

The GKN II reactor building consists of a reinforced concrete shield building, a spherical steel containment vessel, and a reinforced concrete internal structure as shown in Figure 1. No positive structural connections were provided between the interface of the spherical steel containment shell and the base of the internal structure or between the interface of the containment shell and the bowl-shape concrete structure supporting the shell from below. Seismic-induced sliding at these interfaces in the event of a beyond-design-basis earthquake could result in failure of pipe penetrations. The strength factor for the sliding failure was conservatively calculated based on incipient sliding. It is to be noted that substantial slip displacements are required to fail penetrations, and that acceleration levels exceeding that at incipient sliding are required to induce such displacements.

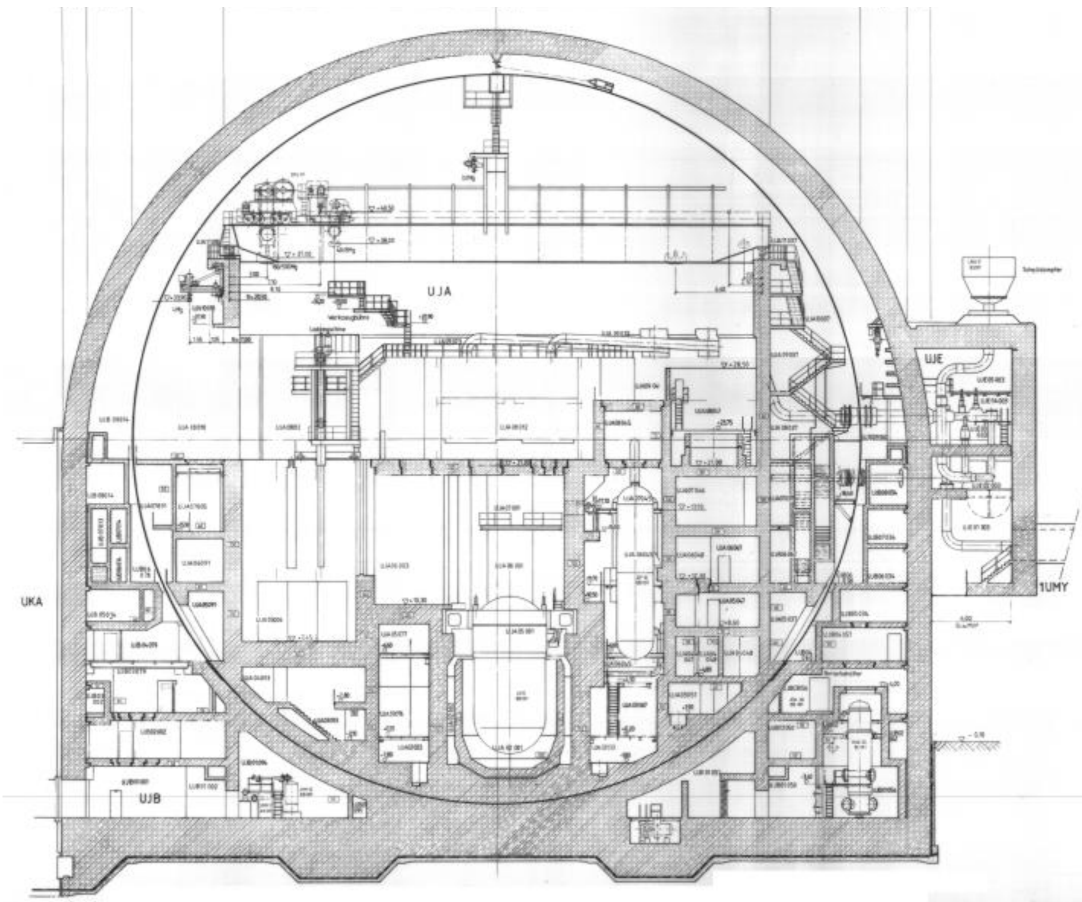

Fig. 1: GKN II Reactor Building Section

Resistance to sliding is provided by friction at the base of the concrete internal structure where the weight of the internal structure provides the normal force. The net normal force is calculated considering the effect of the vertical earthquake component to potentially cancel portion of the gravity. Using the 100-40-40 rule as recommended in EPRI TR-103959 [4], 40% of the vertical seismic force is considered acting concurrent with the horizontal earthquake component. The median static coefficient of friction for concrete on steel is based on test data Rabbat [6], in which an average value of 0.57 was recommended for concrete cast on steel. The median strength factor against sliding was calculated to be 6.4, and the associated uncertainty, which accounted for uncertainty in the median friction coefficient, was estimated at 0.26. Since sliding failure mode is judged to be brittle, no credit was taken for the inelastic energy absorption capability (i.e., the factor of safety is unity). The overall factor of safety, which includes the capacity factor and the structure response factor of the reactor building, was calculated to be 12.88. The median seismic capacity of this failure mode was 1.75g (=12.88 * 0.17g) PGA with associated randomness and uncertainty of 0.32 and 0.43, respectively.

Equipment Seismic Fragilities

Based on the 0.3g PGA screening level, most of the equipment in the SEL was screened from need of further fragility evaluation. Hence, seismic fragilities were performed only for the screened-in electrical equipment and non-qualified mechanical components such as demineralized water storage tanks, the boric acid storage tanks, and the main feedwater storage tanks. Design documents, anchorage drawings, qualification analysis/test reports, and walkdown observations were used in the equipment fragility evaluation to identify potential failure modes. Results from the design seismic response analysis in the form of floor response spectra at locations of equipment mounting were used to estimate seismic demand and variability on the equipment being evaluated.

Example GKN II SSCs fragility results are presented in Table 1. The controlling failure mode for the fragility of each component reflects the weakest aspect of the seismic design as it relates to the safety function of concern for the SSC. That is, it is the seismic failure mode that will result in the seismic failure basic event for the SSC that is modeled in the seismic PSA.

Table 1: Example Seismic Fragility Results

Equipment ID	Description	A_m	β_R	β_U	HCLPF	Failure Mode
LOSP	Loss of Offsite Power	0.3g	0.3	0.4	0.09g	Brittle failure of ceramic insulators.
Containment	Reactor Containment Shell	1.75g	0.32	0.43	0.59g	Sliding at the interface of steel containment and the basemat resulting in damage to pipes at penetrations.
UBA	Switchgear Building	1.2g	0.32	0.42	0.35g	Shear failure of the bottom story shear walls; extensive cracks may result in loss of equipment anchorage.
UMA	Turbine Building	0.56g	0.24	0.32	0.22g	Partial collapse of the building. The turbine building was designed to DIN 4149 for MSK intensity VIII.
BDA	10kV Emergency Bus	1.23g	0.31	0.45	0.35g	Loss of function during shaking (relay malfunction)
		1.71g	0.31	0.48g	0.46g	Loss of function after shaking
BMT10	10kV-660V/380V Auxiliary Transformer	0.55g	0.31	0.26	0.22g	Failure of transformer anchorage
BWH	48V DC Distribution Board	1.04g	0.35	0.62	0.22g	Loss of function during shaking (relay malfunction)
		1.45g	0.35	0.62	0.3g	Loss of function after shaking
LAA10BB001	Feed water Tank	0.21g	0.25	0.29	0.08g	Anchorage failure of the fixed saddle resulting in large displacement of the tank.

CONCLUSIONS

Seismic fragility evaluations of the GKN II SSCs that were credited in the seismic PSA were performed as part of the seismic PSA. The seismic walkdown was performed to screen out seismically rugged components at 0.3g HCLPF capacity. The screening level of the buildings was chosen at 0.5g HCLPF. Seismic fragilities were calculated for the screened-in SSCs using the Safety Factor method. Among the SSE-qualified buildings, the switchgear building had the lowest HCLPF capacity of 0.35g due to large openings in the transverse shear walls in the bottom story. The screened-in SEB qualified equipment that was found to have HCLPF capacity less than the 0.3g are 10kV-660V/380V auxiliary transformers (HCLPF = 0.22g for anchorage failure) and the 40V and 220V DC distribution boards (HCLPF = 0.22g for failure to function during earthquake). The non-seismically qualified components (i.e., demineralized water storage tanks, boric acid storage tanks, and the main feedwater tank) were found to have low seismic capacities with HCLPF capacities in the neighborhood of 0.1g.

Results of the seismic fragility evaluations were input for developing seismic logic models and seismic risk quantification for core damage frequency. The risk study results present the following insights:

- The SSE-qualified SSCs at GKN II have very high seismic capacity relative to the site-specific seismic hazard. Failures of these SSCs do not contribute in any meaningful way to the SDSF and CDF.
- The non SSE-qualified SSCs at GKN II also have, for the most part, high seismic capacity relative to

the site-specific seismic hazard. Only two such items contribute in any meaningful way to the SDSF and CDF:

  - Failure of the feedwater tank is assessed to be the most important seismic failure, but it is still only a small risk contributor.
  - The second important seismic failure is the failure of offsite power, but it is still only a small contributor.

- The primary seismic event contribution to SDSF and CDF is due to the plant shutdown that occurs following the seismic event. This comes from random failures that occur following the plant shutdown. These random failures are essentially the same as those that can occur after any plant shutdown and are the same as those identified as important in the internal events PSA.
- The calculated SDSF and CDF from seismic events at GKN II is very small compared to the SDSF and CDF from internal events and do not contribute in any measurable way to overall SDSF and CDF for GKN II.

In summary, the study has demonstrated that, given the high seismic design capacity of the GKN II SSCs, seismic events do not constitute a credible challenge to the plant. The detailed seismic walkdown and review of design documents for fragility evaluation have further enhanced the seismic safety of the plant. In the walkdown, seismic spatial interaction issues and housekeeping items were identified. With these issues resolved, GKNII has achieved increased safety against seismic hazards.

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