

Insights gained from the Beznau Seismic PSA

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1 ABSTRACT

PSA studies performed for Light Water Reactors (LWRs) have shown dominating risk contributions from seismic events. Also, new seismic hazard studies have calculated higher seismic accelerations than assumed before.

In this paper, the most recent results and insights gained from Seismic Level 2 PSA study of the Beznau NPP are shown. The paper first presents the recent hazard results for the Beznau site. In addition, the important characteristics and methods applied in the site-specific seismic PSA are shown. The study represents a Level 2 study that fully considers containment integrity and that quantifies the Large Early Release Frequency (LERF) for seismic events.

The paper also shows the important risk contributors with respect to the Core Damage Frequency (CDF) as well as with respect to LERF. One main conclusion of the study is that the seismic capacity of the containment represents a key role with respect to the seismic Large Early Release Frequency LERF. In addition, the calculated results indicate that a seismic design of the reactor building of Advanced Light Water Reactors (ALWRs) of 0.5 g HCLPF may be too low even in areas of low to moderate seismicity.

2 INTRODUCTION

PSA studies performed for Light Water Reactors (LWRs) have shown dominating risk contributions from seismic events. There are several reasons for that finding. New Probabilistic Seismic Hazard Analyses (PSHAs) calculate a higher seismic hazard than perceived in the past. In addition, earthquakes represent a common-mode attack on all safety systems including the containment. On the other side, refined methods are currently available in the area of seismic PSA that enable assignment of higher seismic capacities to structures, systems and components.

In this paper, recent results and insights gained from the Beznau Seismic Level 2 PSA study are shown. Beznau nuclear power plant is the oldest operating pressurized water reactor (PWR) in the world. The plant was backfitted extensively during the last two decades by the construction of additional and seismically more robust safety systems. Section 2 gives an overview of the Beznau Nuclear Power Plant and its previous PSA studies.

Section 3 presents the most important characteristics and methods applied in the Beznau Seismic PSA study, for example three-dimensional soil structure interaction analysis using thirty individual time histories. It also presents the results of the actual Probabilistic Seismic Hazard Analysis (PSHA) performed for the Swiss NPPS sites, the so called PEGASOS study.

In Section 4, the important results and insights of the Beznau Seismic PSA study are shown. The median capacities obtained for structures, systems and components by recent methods are compared to results of the earlier analyses performed in the 1980s. The Beznau seismic PSA represents a Level 2 study that fully considers containment integrity and that quantifies the Large Early Release Frequency (LERF) for seismic events. Therefore, Section 4 also shows the most important risk contributors with respect to the Core Damage Frequency (CDF) as well as with respect to the Large Early Release Frequency (LERF).

One main finding of the Beznau seismic PSA is that the seismic capacity of the containment represents a key role with respect to the seismic Large Early Release Frequency LERF. Therefore, Section 5 includes a sensitivity study about the expected seismic LERF of Advanced Light Water Reactors (ALWRs) when assuming the PEGASOS seismic hazard of Switzerland, which is a country of low to moderate seismicity. Section 6 concludes with the important findings of the paper.

3 BEZNAU PLANT AND EARLIER PSA STUDIES

3.1 Beznau Plant

The Beznau plant is located in Northern part of Switzerland and consists of two Westinghouse pressurized water reactors of early design. Unit 1 went into operation 1969 and is actually the oldest operating PWR in the world. Unit 2 started operation in 1971. The net power output per unit is 364 MWe. Both units were backfitted in the early 1990s by the construction of additional safety systems located in a separate bunker building which are fully seismically qualified according to recent standards and which are fully separated from the “old” systems. The seismic design of the new bunker systems corresponds to 0.21 g PGA (equivalent to 0.15 g at the foundation level of the reactor building), while the old plant was designed for an SSE of 0.12 g, but using very simplified methods. The structural design of the new bunker building was mainly driven by aircraft crash load considerations.

This backfit extended the original two-train safety systems configuration to three trains. In addition, the third train is diverse. Figure 1 shows the main systems of the plant as they exist today. All components called "Notst." and the accumulators were added as part of this backfit.

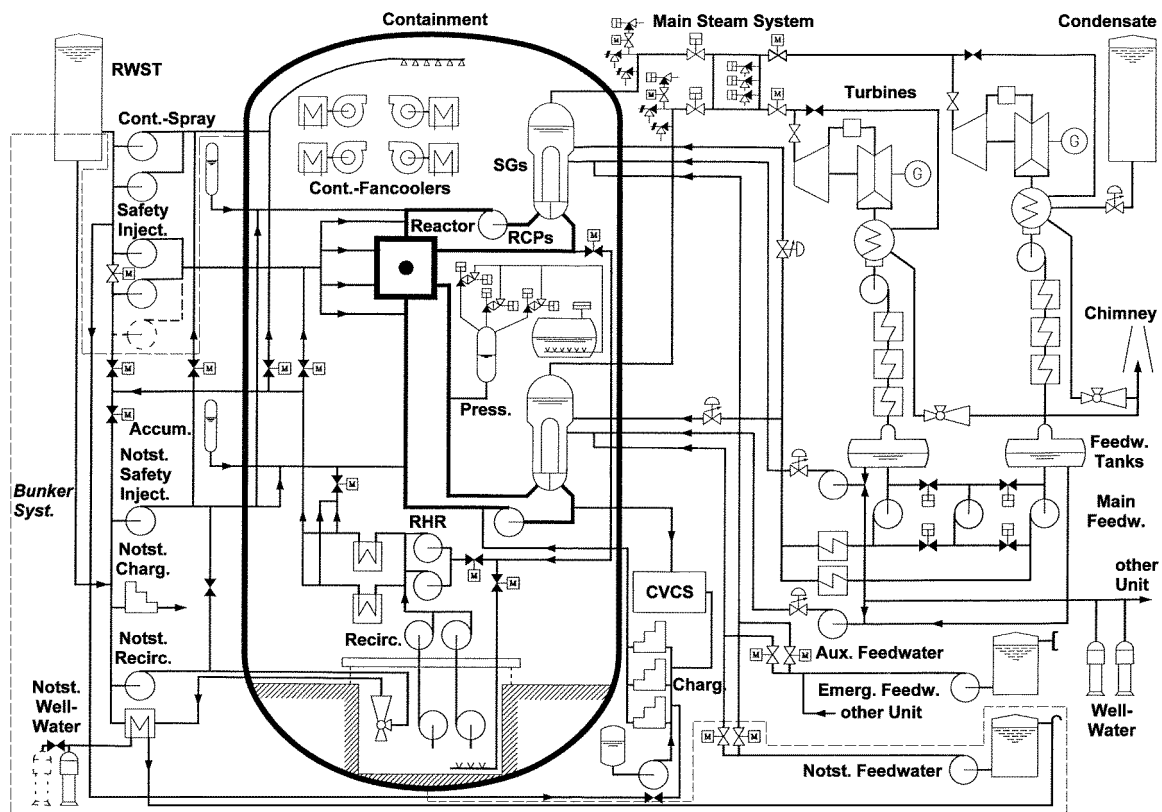


Figure 1. Main Systems of a Beznau PWR Unit

3.2 Beznau Earlier PSA Studies

For Unit 2 of the Beznau plant, a first Level 1 PSA study [PLG 1989] was performed in the mid 1980s that included all relevant internal events, external events (seismic, external floods, high winds, etc.) and internal plant hazards (fires, floods) at full-power modes. This study was updated end of the 1990s [NOK 1999] and was extended to operating modes of low power, hot shutdown, RHR cooling and core unloaded to the spent fuel pit [PLG 1998]. In addition, a Level 2 PSA for full-power modes was performed in 1986 and was updated later [NOK 2002].

4 CHARACTERISTICS OF NEW SEISMIC PSA STUDY

4.1 New Seismic Hazard (PEGASOS)

Switzerland is a country of low to moderate seismicity. The earlier Beznau Seismic PSA study was based on the seismic hazard assessment according to [ETH 1977] and [B&H 1984]. In 2000, the Swiss licensing authorities required to fully renew the Probabilistic Seismic Hazard Analysis (PSHA) for all Swiss NPPs. The new study was called PEGASOS [NAGRA 2004]. The Swiss authorities required the study to be performed according to the SSHAC procedures [NRC 1997] at its highest elaborated Level 4.

Contributors to the PEGASOS project were 21 international experts from Europe and the US. The project was divided into four different subprojects: Source Models (four groups of three experts each), Ground Motion Models (five experts), Site Response (four experts) and Hazard Computation.

Figure 2 shows the PEGASOS mean, median and 84th-percentile hazard curves for the Beznau site at the foundation level of the reactor building. Also shown in Figure 2 are the old Beznau hazard curve and another modern hazard curve for the Paks NPP [GeoRisk 2000], which is a site of similar seismicity as Beznau.

Figure 2. Seismic Hazard for Beznau (PEGASOS and Old Analysis) and for Paks Site

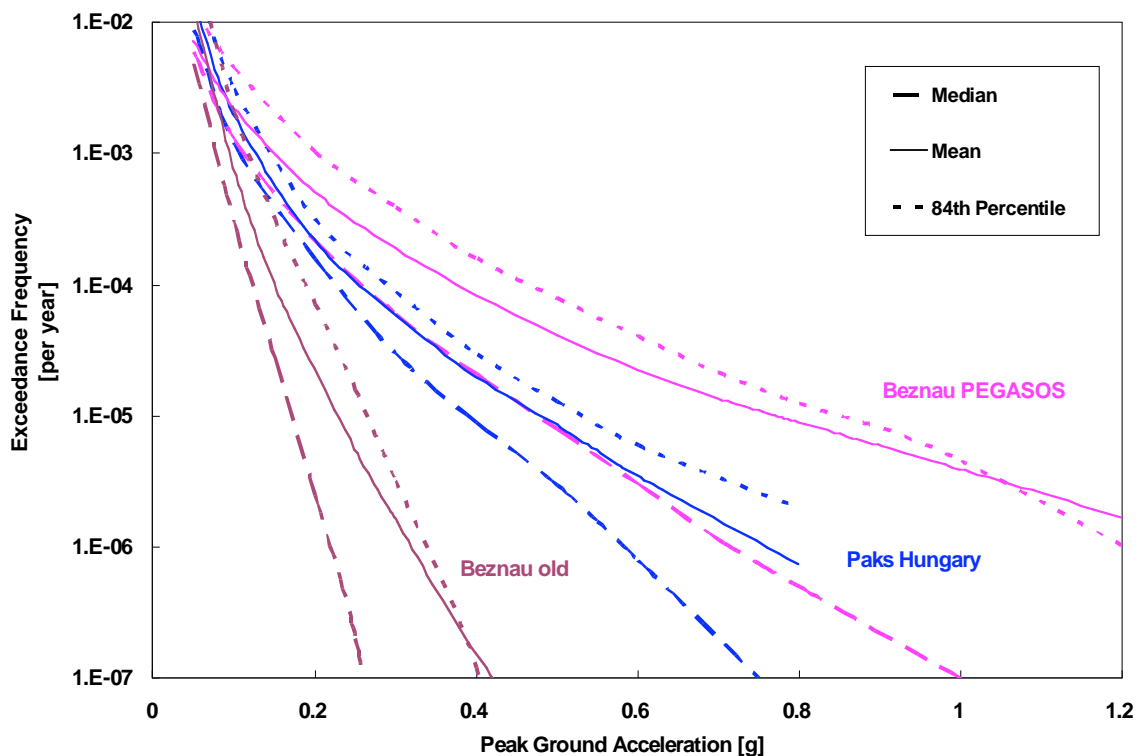


Figure 2 shows that the old Beznau hazard evaluation was optimistic compared to the more recent study for the Paks Site. However, the PEGASOS hazard appears to be extraordinarily high compared to other modern PSHA studies. One of the main reasons for this is the large uncertainty range of the hazard, which drives the mean hazard curve up to unrealistically high values.

A PEGASOS refinement project was started in the meantime to upgrade the PEGASOS study. Until completion of PEGASOS refinement, the Swiss authorities agreed to use in all Swiss Seismic PSA studies the PEGASOS hazard curves with a correction factor to reduce the accelerations by 20 percent.

4.2 Probabilistic Seismic Response Analysis

For all relevant buildings of Beznau Unit 2, a detailed probabilistic seismic response analysis was performed [ABSG 2007a]. The main characteristics of this analysis are:

- Use of 30 real time histories of European Earthquake Catalog of Magnitudes 5.0 – 6.4, distance 0 – 125 km.
- Modification of these time histories to match in summary the PEGASOS Uniform Hazard Spectrum at 1.E-05 y-1 exceedance frequency, scaled to 1 g PGA (see Figures 3, 4).
- Use of three-dimensional soil structure interaction analysis code SASSI [ABSG SASSI]. For the SSI analyses, the soil properties are consistent with the seismic level defined for 1.E-05 y⁻¹ exceedance frequency.

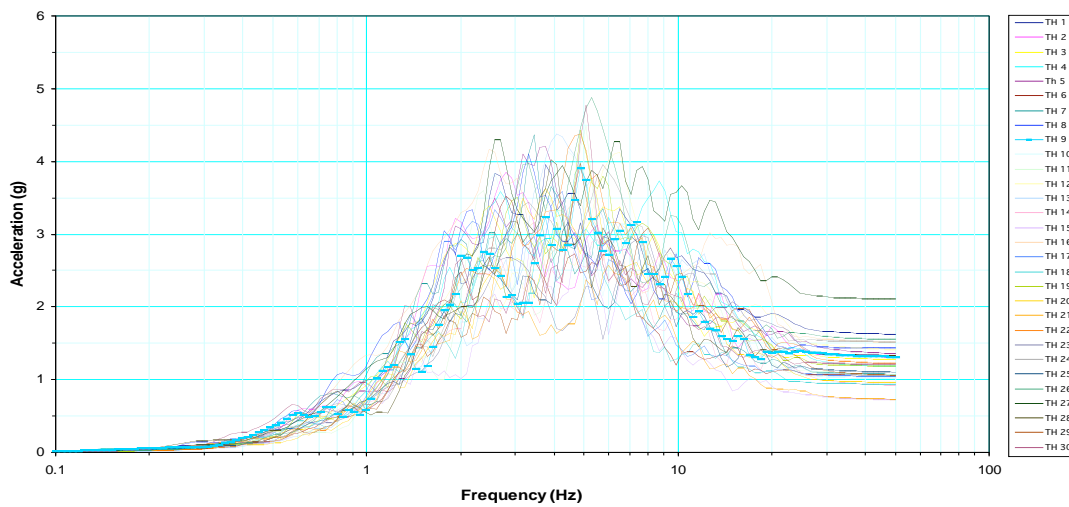


Figure 3. Summary of 30 Time Histories Used

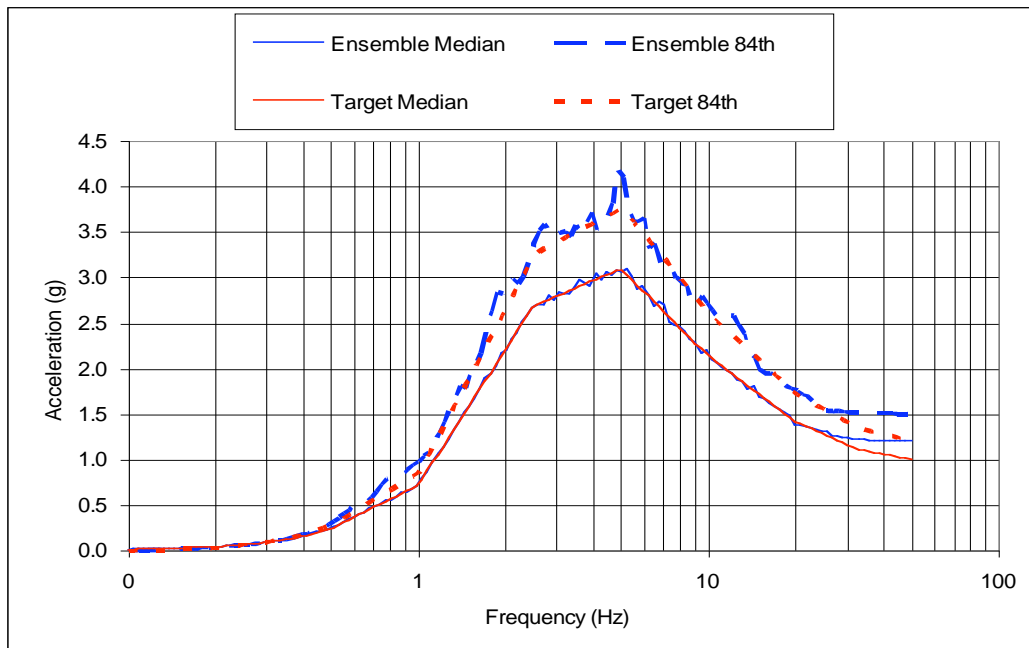


Figure 4. Resulting Median and 84th-Percentile UHS from Time Histories compared to PEGASOS Target

As a result of this probabilistic seismic response analysis, probabilistic floor response spectra were obtained for each building and each floor level. Figure 5 compares, at the operating floor of the reactor building, the probabilistic floor response spectra with the deterministic plant design spectra, scaled to 1 g PGA, free field acceleration.

As shown in Figure 5, the probabilistic SSI analysis using 30 time histories results in a reduction factor of the maximum accelerations of at least 1.5 compared to the design. Figure 6 shows the same comparison for the highest floor of the bunker building, where the reduction is even higher.

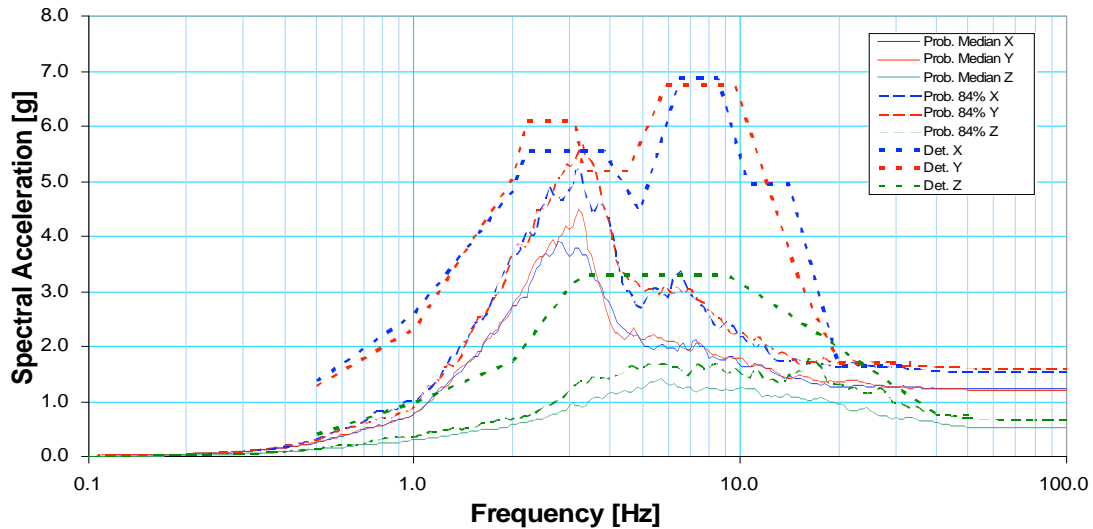


Figure 5. Probabilistic Floor Response Spectra (5% Damping) for Operating Floor of Reactor Building compared with Deterministic Design Spectra

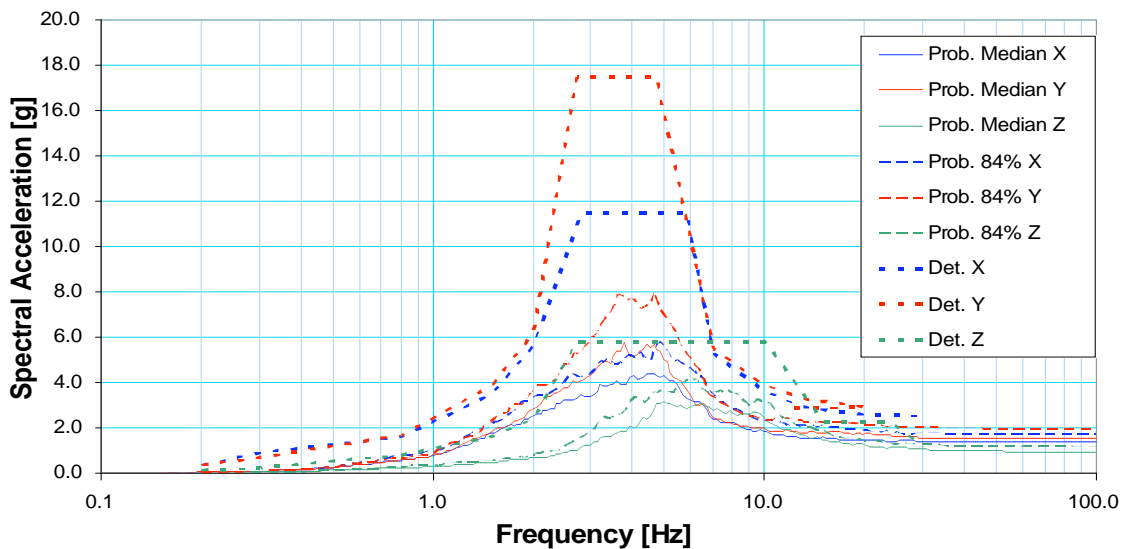


Figure 6. Probabilistic Floor Response Spectra (5% Damping) for Highest Floor of Bunker Building compared with Deterministic Design Spectra

4.3 Plant Walkdown and Screening Criteria

The Beznau seismic walkdown started with a Seismic Equipment List (SEL) that included around 1400 individual components. Among these were about 400 manual valves and check valves of a size lower than 10 inches. These were considered as part of the piping systems and therefore were excluded from the final SEL.

As a result, the final Seismic Equipment List included 992 individual components. The SEL also contained all equipment that is part of the containment system to include a Level 2 consideration for LERF.

However, due to the high PEGASOS hazard, the screening criteria according to EPRI NP-6041-SL [EPRI 1991] would correspond to an exceedance frequency of about 1.E-05 per year and therefore could not be used. Therefore, the following approach was used for screening:

- From the 992 components of the SEL, only about 200 were fully screened during the walkdown that were found to be extraordinary robust.
- From the remaining 790 components, also those that fulfilled a screening criterion of 2 g HCLPF local Spectral Acceleration were retained in the database. For these components, individual fragilities were developed by transferring the local HCLPF capacity to a median free field capacity using the building amplification factors obtained from the probabilistic response analysis.

4.4 Individual Fragilities and Plant PSA Model

From the 790 components of the SEL that were not fully screened out, the following set of fragilities were developed:

- Generic fragilities were applied to the installations of the offsite grid.
- 33 individual fragilities analyses were performed for a total 280 components.
- For the remaining 440 components that fulfilled the screening criterion of 2 g local Spectral Acceleration, floor related median capacities were developed based on the amplification factors of the probabilistic response analysis.

As a result, 790 individual fragility values were developed [ABSG 2007b], while many of them are identical due to the same floor level. For incorporation of these fragilities into the PSA model, they were merged to 120 fragility families. These 120 fragility families were implemented in 52 individual seismic top events into the linked event tree model of the Beznau plant using the RISKMAN Software [ABSG 2007c]. As a result, the seismic event tree includes about 300 million individual seismic sequences. Each of them is coupled with the “normal” PSA model for internal events.

5 RESULTS OF UPDATED SEISMIC PSA

5.1 Comparison of New and Old Capacities

Table 1 illustrates the new median and HCLPF capacities for the most important buildings, compared to the values of the earlier analyses of the 1980s. Table 2 shows the new median and HCLPF capacities for the most important mechanical and electrical components, again in comparison with the old analyses. In last two columns of these tables, higher values of the new analyses are marked green, lower capacities in red.

As it can be seen from Tables 1 and 2, the new and refined analyses generally result in higher capacities, while there are some specific exceptions.

Table 1. Median and HCLPF Capacities of Specific Buildings in Comparison with SSE of 0.15 g and with Old Results

	Median / SSE	HCLPF / SSE	Median / Median _{old}	HCLPF / HCLPF _{old}
Reactor Building local	7.5	2.4	1.1	1.3
Aux. Building E (MCR)	5.7	2.5	1.4	2.8
Aux. Building A	4.0	1.6	0.6	0.8
Aux. Building B (Pool)	22.1	12.0	-	-
Notstand Building	26.3	11.1	4.8	4.6
RWST Building	7.7	3.2	0.7	1.1
Hydro Turbine Building	0.7	0.4	0.2	0.6

Table 2. Median and HCLPF Capacities of Specific Components in Comparison with SSE of 0.15 g and with Old Results

	Median / SSE	HCLPF / SSE	Median / Median _{old}	HCLPF / HCLPF _{old}
RPV	13.3	6.0	1.1	2.2
CRDM	12.4	4.3	1.5	1.6
SG	8.7	3.9	0.7	1.7
RWST	9.3	4.4	1.0	1.7
Accumulators	7.7	3.6	2.0	2.3
Main FW Tanks	1.1	0.5	0.4	1.1
SW Piping inside Cont.	15.1	4.1	2.3	2.1
Cont. Isolation Valves	8.2	3.3	0.7	1.0
Notstand AC	9.0	2.7	1.5	1.2
Notstand DC	8.4	3.1	1.8	1.8
Notstand Actuation	9.7	3.5	2.1	2.1
Notstand Mechanical	7.7	3.5	2.0	2.3

5.2 Cost Effective Upgrades

The first results of the new seismic PSA showed relative high contributions to the seismic LERF. As a result, relative simple and cost effective upgrade measures were identified to improve plant safety. These upgrades will be realized in next years. The most important ones are:

- Move of some containment isolation valves from outside containment to a location inside.
- Upgrade of anchorage of some mechanical equipment inside containment such as containment fan cooler heat exchangers or instrument air receiver.

Due to these cost effective measures, the seismic LERF is reduced by more than a factor of 2. The following PSA results implicitly consider these upgrades.

5.3 Contributions to CDF and LERF

Figure 7 illustrates the contributions of all initiator groups to CDF and LERF for all modes of operation. All events were investigated in all modes of operation, for example seismic, fires, floods, severe weather. As it can be seen from this figure, seismic events contribute 68% to CDF and 96% to LERF for power modes. Even during shutdown modes, the contribution from seismic events is considerable. Seismic is the most important contributor to CDF, but it is the completely dominating hazard with respect to LERF.

Figure 8 illustrates the contributions of the different seismic acceleration levels to CDF and LERF for power modes. The individual seismic accelerations are expressed in spectral acceleration, which corresponds to a response frequency of 5 Hz. Expressed in spectral acceleration, the plant design SSE is equivalent to 0.51 g.

As shown in Figure 8, the dominating risk contribution results from seismic events of a spectral acceleration between 1.5 g and 3.5 g (corresponds to PGA between 0.4 and 1.0g), which is between 3 and 7 times the plant SSE.

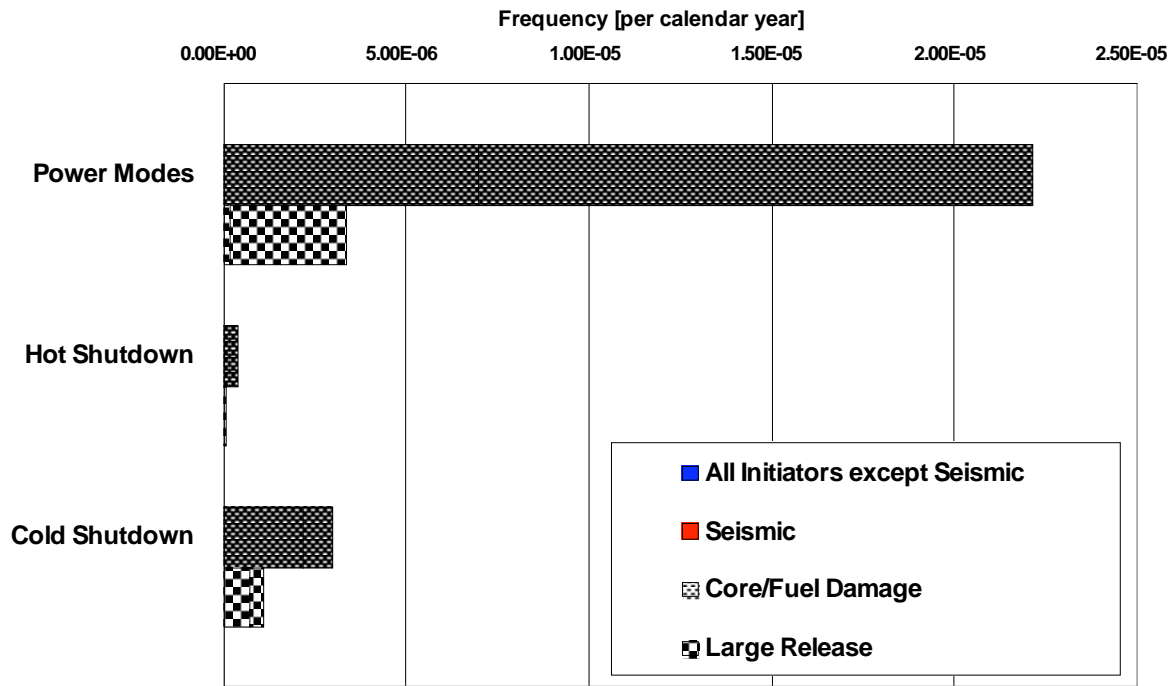


Figure 7. Beznau CDF and LERF from Seismic and Non-Seismic Events for All Modes of Operation

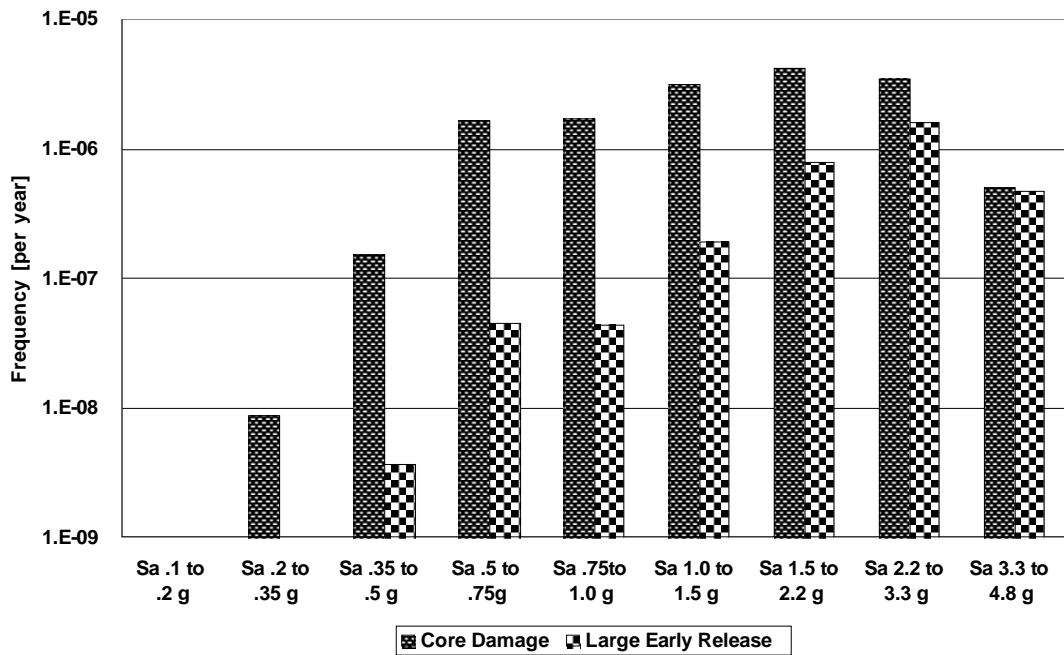


Figure 8. Contributions of Seismic Acceleration Levels (Spectral Acceleration 5 Hz) to CDF and LERF of Power Operation

Figure 9 illustrates the Fussel-Vesely-Importances of all structures, systems and components with respect to the LERF of power operation. As it can be seen from Figure 9, the seismic capacity of the containment and its isolation system plays a key role with respect to the risk of large releases.

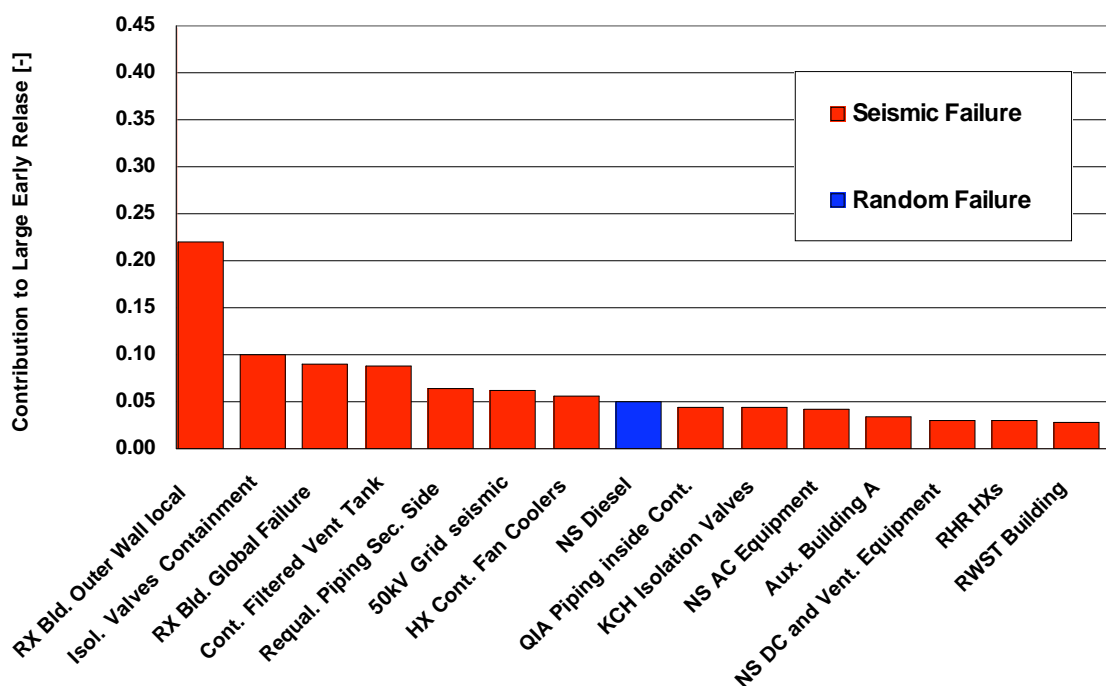


Figure 9. Contributions of SSCs to LERF of Power Operation

6 OUTLOOK ON NEW REACTOR DESIGNS

Based on the insights of the Beznau seismic PSA study, a sensitivity study was performed with respect to the seismic LERF contribution of advanced reactor designs in assuming the PEGASOS hazard, which is representative for a country of low to moderate seismicity.

The following assumptions were made in this sensitivity analysis:

- Two cases of 100 percent PEGASOS hazard and of 80% PEGASOS (reduction of the PEGASOS accelerations by 20 percent).
- Seismic capacity of the reactor building and its isolation system: several cases of HCLPF between 0.4 g and 0.8 g PGA.
- Assumed uncertainty parameters of reactor building capacity: $\beta_R = 0.2$ and $\beta_U = 0.3$.
- Assumption that failure of the reactor building directly leads to LERF.

Under these assumptions, the seismic LERF of a reactor in country of low to moderate seismicity such as Switzerland is expected as illustrated in Table 3.

Table 3. Seismic LERF for Different Reactor Building Capacities and PEGASOS Hazard

	HCLPF 0.4 g	HCLPF 0.5 g	HCLPF 0.6 g	HCLPF 0.7 g	HCLPF 0.8 g
80% PEGASOS	3.6E-06 y ⁻¹	1.3E-06 y ⁻¹	4.7E-07 y ⁻¹	1.9E-07 y ⁻¹	7.8E-08 y ⁻¹
100% PEGASOS	9.3E-06 y ⁻¹	3.6E-06 y ⁻¹	1.5E-06 y ⁻¹	7.0E-07 y ⁻¹	3.2E-07 y ⁻¹

As a conclusion of this sensitivity study, a HCLPF capacity of the reactor building of 0.5 g PGA may not be adequate for Advanced Light Water Reactors (ALWRs) to fulfill the safety goal of a LERF lower than 1.E-06 per year in a country of low to moderate seismicity such as Switzerland.

7 CONCLUSIONS

Based on the results presented herein, the following conclusions can be drawn:

- More recent methods of seismic PSA such as three-dimensional soil structure interaction analysis using a set of time histories result in higher seismic capacities of structures, systems and components than earlier methods.
- The higher capacities however may be compensated by higher seismic hazard values that result from actual Probabilistic Seismic Hazard Analyses (PSHAs).
- The effort to perform a realistic and complete seismic PSA study is high since screening capabilities are very limited with respect to the high seismic hazard values.
- A seismic PSA may show simple and cost effective measures to improve plant safety.
- Even in countries of low to moderate seismicity, seismic events represent an important contributor to the core damage frequency (CDF).
- The reactor building seismic capacity represents a key role with respect to the risk of large releases (LERF) for seismic events.
- Seismic events represent a dominating contributor to LERF.
- When assuming the PEGASOS hazard of Switzerland for countries of low to moderate seismicity, a reactor building HCLPF capacity of 0.5 g is not sufficient to fulfill the safety goal for Advanced Light Water Reactors of a LERF lower than 1.E-06 per year.

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