Update of the Plant-specific Seismic PRA of NPP Goesgen – Risk Model, Results and Insights

J.-U. Klügel[a], A. Nykyforchyn[a], and D. Kancev[a]
[a]NPP Goesgen, Daeniken, Switzerland

Abstract: In 2016, an ordinance of the Swiss Nuclear Safety Inspectorate completed the update of the probabilistic seismic hazard assessments for Swiss NPP sites According to the ordinance the new hazard provides the basis of a re-assessment of seismic risk for all Swiss NPPs besides a deterministic re-evaluation of plant seismic safety. NPP Goesgen developed a new seismic risk model, which on one hand captures adequately the complexity of the plant design as well as the different plant modifications enhancing seismic safety and on the other hand, allows for reasonable computation times on a standard multi-processor workstation. Eight initiating events model the seismic hazard, which is represented as discrete probability distribution by a set of 100 hazard curves. The hazard model captures the range of accelerations between 0.07g and 7.99g. Approximately 170 calculation groups for which a re-assessment of the seismic fragility based on the development of probabilistic in-structure floor response spectra was accomplished model the safe shutdown list of the plant. The model as well as results from the fragility analysis are presented. The quantification of the risk model confirmed the safety benefit of recent seismic upgrades, especially of the installation of a seismic safe shutdown system at the plant.

Keywords: Seismic PRA, Fragility Analysis, Soil-Structure Interaction, Seismic Shutdown System

1. INTRODUCTION

NPP Gösgen is a three-loop PWR (vendor KWU) commissioned in 1979. The first complete PRA (level 1, level2, power and non-power operation, external and internal events and hazards) was completed in 1994. In May 2016 the process to update the probabilistic seismic hazard assessments for the Swiss nuclear power plant sites terminated by an ordinance issued by the Swiss regulatory body. The regulatory authority, ENSI, defined the new hazard based on a supporting PSHA performed in compliance with the US SSHAC level four procedures. The results of the hazard assessments are available in form of uniform hazard spectra (UHS) for different annual frequencies of exceedance, accompanied by corresponding deaggregation results. The latter provide information on magnitude and location of the controlling earthquakes. Besides a deterministic reassessment of the overall seismic safety of Swiss NPPs, the ordinance requires an update of the seismic PRA to include the new seismic hazard. NPP Goesgen launched a large-scale safety re-assessment project that also includes the update of the seismic PRA.

The changed seismic hazard as well as numerous seismic upgrades performed by NPP Goesgen required a complete remodeling of the structure of the seismic PRA to obtain a representative risk model. The work performed included an update of the seismic fragility functions for key risk relevant systems, structures and components (SSC).

The risk model developed, important results and insights gained from the project are presented in the following sections.

2. OVERALL METHODOLOGY

The key steps of the methodology are as follows:

- Execution of a probabilistic seismic hazard analysis (PSHA) to develop a plant-specific seismic hazard for the engineering parameters of interest. This task was completed by the ordinance issued by the Swiss regulatory body (ENSI) specifying the hazard to be applied.

- Development of a safe shutdown list of structures, systems, and components (SSC) relevant for the mitigation of the consequences of an earthquake and the functions supported by these SSCs. A safe shutdown list, which is regularly updated, is available at NPP Goesgen since the development of the first PRA completed in 1994. The list was expanded as a part of safety re-evaluation projects performed in the aftermath of the Fukushima accident.
- Assessment of structural capacity of the SSCs with respect to the failure modes challenging the requested safety and support functions. For most of the SSCs fragility functions, analysis results were available with respect to previous seismic hazard assumptions. A comprehensive update is necessary to comply with the increased requirements issued by the regulatory authority with respect to fragility analysis.
- Development of a plant-specific plant logic model and implementation into the plant specific PSA. A completely new logic model had to be developed to keep track with the large amount of plant modifications while still keeping the size of the model in a quantifiable on a standard multi-processor PC form.
- Adjustment of Human Reliability Analysis (HRA) to consider the impact of seismic events on human performance.
- Quantification of the model.
- Sensitivity and uncertainty analysis

3. RESULTS OF PSHA

The seismic hazard defined by ENSI originally bases on two precursor SSHAC Level 4 [1] PSHA studies, the PEGASOS project [2] and the PEGASOS Refinement Project (PRP) completed by Swiss utilities in 2013. The hazard deaggregation of the results of the PRP showed that large historical earthquakes like the Basel earthquake of 1356 were insufficiently captured. Therefore, ENSI commanded to adjust the seismic source model increasing the contribution of higher magnitude earthquakes to the study results. The resulting hazard is denoted ENSI-2015. The results of the hazard assessments are available in form of uniform hazard spectra (UHS) for different annual frequencies of exceedance, accompanied by corresponding deaggregation results and a set of discrete hazard curves (100) for different spectral frequencies including peak ground acceleration (PGA). The latter provide information on magnitude and location of the controlling earthquakes. Figures 1 and 2, correspondingly, show the uniform hazard spectrum for a frequency of exceedance of 10^{-4}/a and the hazard curve for PGA including the uncertainty bounds. Additionally, deaggregation results are available allowing defining the controlling earthquakes. The hazard is driven by moderate earthquakes (Magnitude 6-6.3) which "move" closer to the station site with decreasing frequency of exceedance (from 20 km to about 10 km distance). Therefore, the seismic energy of the controlling earthquakes is rather low. Geological and geomorphological investigates as well as the evaluation of historical and instrumental seismicity did not identify the existence of faults near the Goesgen site capable for producing such earthquakes. The resolution level of the investigations performed is around magnitude 5. The fault system that caused the historical earthquake of Basel (1356, estimated magnitude range between (6.2 (in France) and 6.9 (upper estimate)) is located at 30 -35 km distance from the plant site.

Figure 1: Uniform Hazard Spectrum, Frequency of Exceedance 10^{-4}/a– ENSI 2015

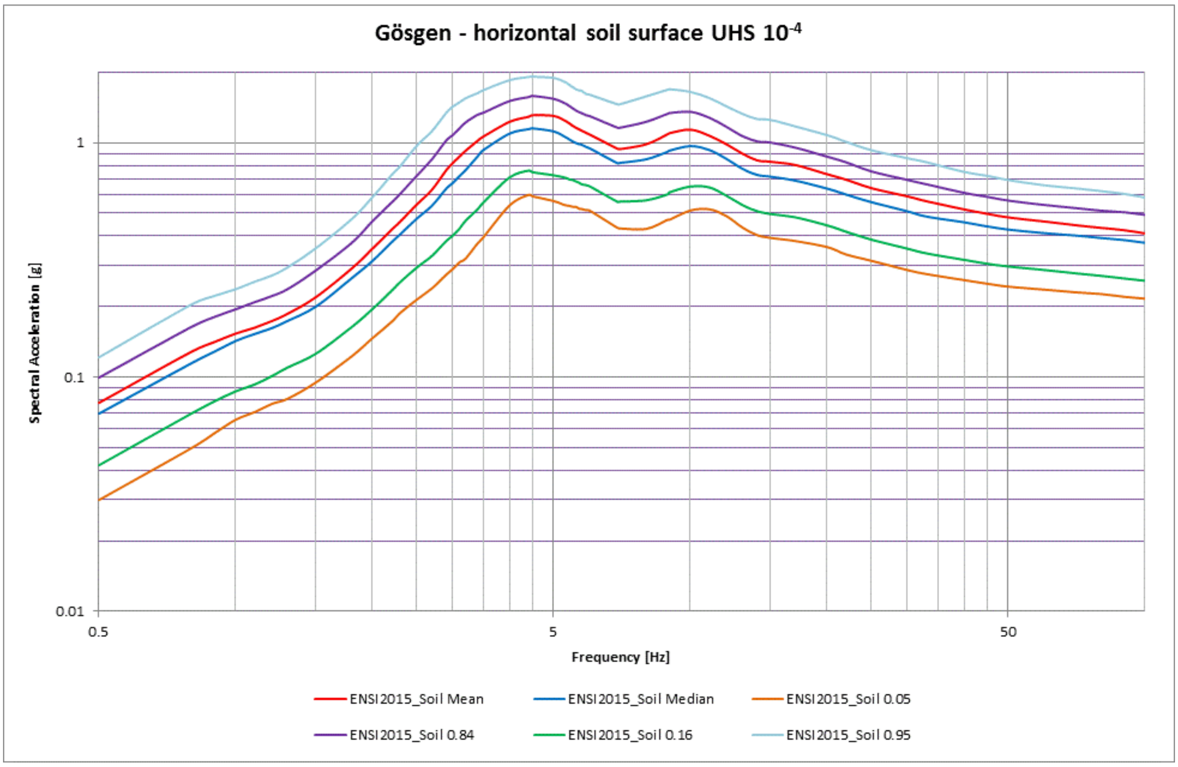
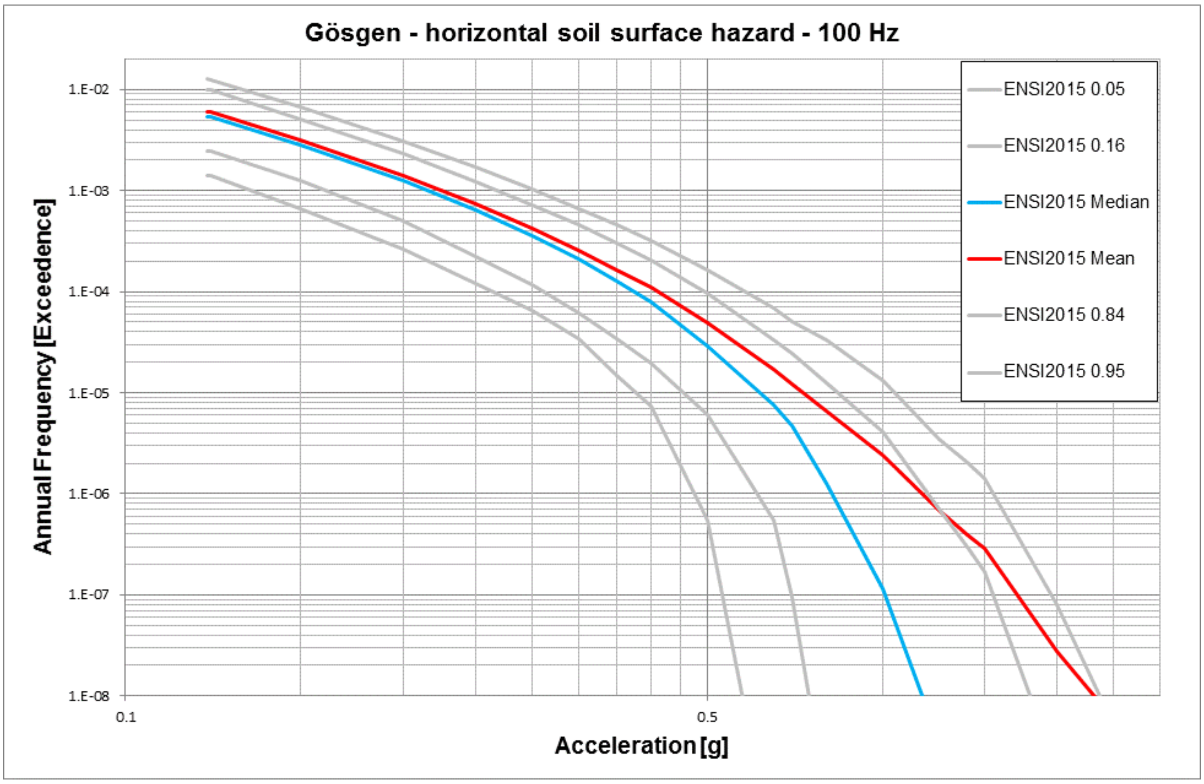


Figure 2: Seismic Hazard Curve (PGA-100Hz) – ENSI 2015



For the seismic PRA the results of hazard analysis were converted into a set of eight initiating events, defined as follows:

Table 1: Seismic Initiating Events

Initiating Event	Lower Bound, PGA [g]	Upper Bound, PGA [g]	Frequency, [1/a]
SEIS1	0.0701	0.125	3.81×10^{-3}
SEIS2	0.125	0.25	1.68×10^{-3}
SEIS3	0.25	0.4	3.09×10^{-4}
SEIS4	0.4	0.6	8.50×10^{-5}
SEIS5	0.6	0.8	1.69×10^{-5}
SEIS6	0.8	1.1	4.96×10^{-6}
SEIS7	1.1	1.7	1.21×10^{-6}
SEIS8	1.7	7.99	8.55×10^{-8}

The initiating events SEIS1 and SEIS2 cover the acceleration range corresponding to the original design basis of NPP Goesgen. Initiating event SEIS 3 covers the seismic design extension achieved by diverse projects aimed at the increase of the seismic capacity of safety-important SSCs before and after the Fukushima accident.

4. UPDATE OF PLANT-SPECIFIC FRAGILITY ANALYSIS

4.1. Methodology

The plant specific fragility analyses were performed. These were based on the earlier fragility analyses, which were conducted after the Fukushima accident. The SSC capacities were updated to account for the new seismic hazard UHS spectra. The procedure consists of following steps:

- Update of the SSC list by removing obsolete components and adding new components
- Reevaluation of the earlier analyses by applying the same methodology described in [4] and [5].
- Reassessment of the fragility of SSC that received seismic upgrade in the last years.
- Scaling of the seismic capacities to the new hazard
- Recalculation of the fragility functions for SSC with high risk contribution.

4.2. Seismic walkdowns

The verification of seismic safety of the components and systems in KKG has been supported in recent years in several plant walkdowns. Structures, components and systems have been inspected for their seismic robustness regarding the screening level PGA = 0.6 g. Most of the safety relevant and important components were found to have a robust design and be rigidly anchored, so that they could be screened out from further analyses. Several components and pipes as well as some masonry walls were nailed down for detailed seismic analyses. This included typically anchorage of pumps and motors, piping supports and support structures for electrical cabinets.

4.3. Scaling of seismic capacities

The reassessment of the seismic capacities was performed to account for the different shape of UHS spectra in ENSI-2015 hazard in comparison to the PEGASOS 2004 spectra, which were used in the earlier seismic fragilities. The median capacity was scaled by the factor

$$A_{m\,ENSI2015} = A_{m\,PEGASOS}\;\frac{PGA_{ENSI2015}}{PGA_{PEGASOS}}\frac{S_{A\;PEGASOS}}{S_{A\,ENSI2015}}$$

Where $PGA_{PEGASOS}$ and $PGA_{ENSI2015}$ are the respective peak ground accelerations, $S_{A\_PEGASOS}$ and $S_{A\_ENSI2015}$ are the spectral accelerations, which are relevant for the components integrity. For most components, the relevant spectral accelerations are related to the dominant natural frequency of the corresponding structure. For the containment building and emergency diesel building these frequency lie between 3 and 5 Hz, where the scaling factor lies between 0.83 and 1.0. For few components with lower natural frequency than the structure frequency, additional scaling was implemented.

4.4 Probabilistic Floor Response Spectra

For the SSC with high risk contribution the seismic capacities were recalculated based on the recently developed probabilistic floor response spectra. These refined seismic spectra were calculated based on the new 3D detailed models of the structures with soil structure interaction analyses. Median UHS at annual frequencies of exceedance 10^{-4}/a and 10^{-5}/a were selected. 30 sets of UHS compatible statistically independent time histories were generated based on the real time histories records from the RESORCE database and the seismic hazard background for the Gösgen site. In the dynamic calculations, the properties of the soil-structure, mainly their stiffness, masses and damping, are probabilistically scattered according to Latin Hypercube variation. With these, 30 probabilistic calculation models are generated from the basic models. Combined with the 30 sets of excitation time curves, a probabilistic ensemble of FRS and relative displacement is calculated. The results are statistically evaluated and presented as mean, median, 5%, 16%, 84% and 95% fractiles. The individual procedures follow the US NRC Standard Review Plan (SRP) and EPRI guidelines [4,5,6].

With refined structural modeling less conservative floor response were obtained for all structures. The PGA as well as the maximum spectral accelerations were reduced by up to 30%, which had an immediate effect on the increase of the seismic capacities.

4.5 Fragility analyses

The fragility analysis is based on median-centered parameters and distributions according to the guidelines of EPRI.

The HCLPF (High Confidence of Low Probability of Failure) value of the stability of the SSC under Seismic load is defined as the 95% confidence level for 5% probability of default [6]. The median HCLPF50 results as a multiplication of a median value for the 95% confidence level with the factor for a 5% probability of failure.

$$HCLPF_{50} = A_m e^{-1.65(\beta_R+\beta_U)}$$

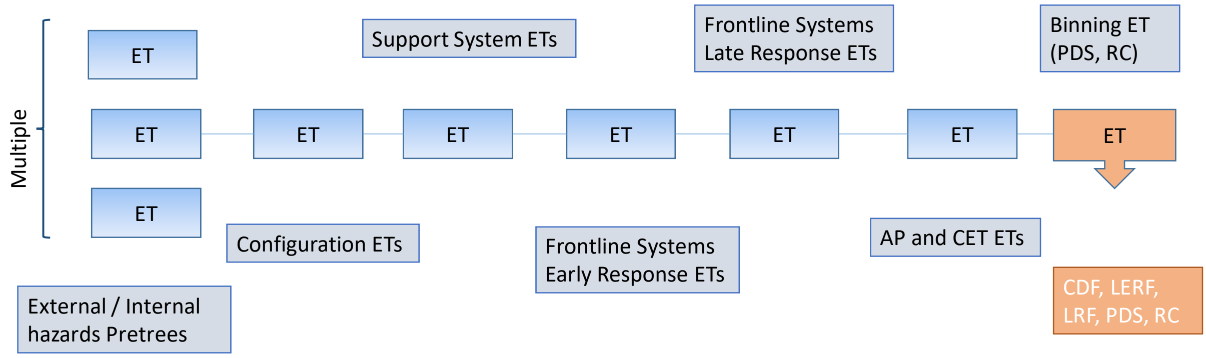
A_m Median capacity of SSCs
β_R Log standard deviation of randomness
β_U Log standard deviation of uncertainty

5. PLANT LOGIC MODEL

5.1. Overall PRA model structure

KKG uses the RISKMAN™ software (large event tree / medium size fault tree approach) for its PRA. The large event tree approach allows for an easy integration of external events into the risk model. KKG uses a linked level 1/ level 2 PRA model for power operation modes as well as for non-power operation modes (operation at reduced power, different types of plant shutdown operation). According to the regulatory requirements in Switzerland, the integrated model covers all types of natural hazards, external and internal (e.g. fires, floods) industrial accidents as well as the traditional list of internal events. The model also covers dependent combinations of hazards/events like seismically induced fires or floods. Out screening of events or combinations, if any, is preferably based on the analysis of the impact of event combinations on plant safety. Physically feasible combinations with synergetic effects on plant safety are included in the analysis by bounding accident scenarios capturing the accident consequences on plant risk in a conservative way. This approach can easily be utilized by using a large set of linked event trees. Several functional event tree groups are used for modeling. The largest functional group, the general transient group, modeling transients (including ATWS) and the plant response for LOCA accidents (of external or internal causes) includes 21 linked event trees. The following figure shows the typical configuration of a functional event tree group as used for the quantification of external and/or internal hazards:

Figure 3: Typical Functional Event Tree (ET) Group – External Events



The general structure of the PRA-model takes account of the dependencies between support and frontline systems as well as between different support systems and different frontline systems (e.g. shared equipment). Operator actions and the dependencies between different actions are also modeled explicitly in the set of linked event trees. A special seismic event tree (pretree) models the impact of seismic initiating events on plant equipment and evaluates the probability of failure for all top events of modeling interests. By a set of logic rules the boundary conditions for plant operation and for the state of support systems (failed, success, partially failed (e.g. for multi train systems) for each of the seismic initiating event are set correspondingly. This includes also modeling of the impact of seismic events on operator actions (post-initiator and accident management actions). Both, the psycho-shock model prescribed by ENSI for plants without seismic shutdown systems or accident sequences with failed seismic shutdown system, as well as a performance shaping factor approach (additional performance shaping factor deteriorating human behavior after an earthquake) can be modelled. Thus, functional dependencies and correlational effects of seismic failure with respect to the failure of functional system chains in conjunction with the associated operator actions are modeled straight forward and do not require special modeling techniques.

5.2 Seismic Model

As shown in Figure 3 external events are integrated into the overall PRA model structure by corresponding pretrees. The latter serve to define the configuration of the plant model addressing the physical impacts of external events on plant systems and operators via a special set of Boolean logic rules. NPP Goesgen developed a special seismic event tree in an iterative procedure to ensure sufficient numerical accuracy avoiding an overly conservative model of the multi-redundant plant safety systems (6 x 100% for Loss of offsite power) and satisfactory computation speed on a standard multi-core workstation. To achieve the latter the initial size of the seismic event tree was reduced from 45 to 37 top events (TEs). The first of the top events questioned represents a logical switch allowing non-seismic initiating events to bypass the seismic event tree. The other TEs are functional top events questioning for the availability of specific required functions or for structural failures of buildings. Included are for example the reactor building collapse leading to direct core damage and an early release of radioactivity, reactor pressure vessel or large component failure leading to an excessive LOCA, the 6 train safety system which is subdivided into 3 subsystems based on the available spatial separation. One of the subsystems represents the special emergency safety system (2 x100%, SBO system) located in a bunkered building. Separate functional TEs are defined for modeling frontline and support systems. Support systems are subdivided in electrical and I&C support functions. Top events used for modeling the electrical support systems include all AC and DC power supplies (including diesel generators with their associated auxiliary equipment, bus, and cabinets, batteries, 220 V system and 24/48 V systems, overall 6 redundancies). Top events used for modeling mechanical support systems include service water system (2 x 100% water intakes), well water system (2 x 100%), essential service water system, the intermediate closed loop component cooling system with the associated equipment (cooling pumps, motor-operated valves, heat exchangers and connecting pipework, diesel fuel tanks). Top events used for modeling I&C support systems cover the reactor protection system and the engineered safeguard system with their equipment. Frontline systems modeled, include the emergency and special feedwater systems, the ECCS, the RHR system functions, and the hardware needed for accident and severe accident management. Each of the seismic top events comprises several seismic components representing single plant components or component groups with the same or similar functional impact in case of failure. The fragility functions derived from the detailed fragility analysis are input for the RISKMAN™ fragility module. This module calculates the conditional failure probability of each seismic top event given a specific initiator. Totally 171 seismic model components with different fragility functions are defined representing approximately 5000 SSCs in the seismic shutdown list of the plant. LOCA conditions inside and outside the containment are modeled by separate top evens as well as steam line breaks or leaks leading to a depressurization of the secondary circuit. For some SSCs, more than a single failure mode is considered. For example, for the reactor building the first failure mode consists in strong non-linear deformation causing a bypass LOCA scenario, while the second failure mode associated with a significantly lower probability of failure consists in a collapse type failure mode.

A special, non-seismic top event models the availability of the new seismic shutdown system by a fault tree. The seismic impact on operator actions is modeled by as separate top event. The "psycho-shock" model described in guideline ENSI-A05 is applied in all cases then the seismic shutdown system is disabled. Analysis has shown that the seismic shutdown system (triggered at low accelerations, PGA about 0.02g) has a positive effect on the timeline of any transient caused by an earthquake. The time available for post-accident actions (Type C and Type D (accident management actions using mobile equipment)) is increased. The dependency of operator actions on hardware availability is directly modeled by the corresponding logic rules of the integrated PRA model. Hence, the boundary conditions for operator actions after successful plant shutdown are in general more favorable than in accident situations caused by internal events. Nevertheless plant model considers an additional negative impact on human performance which is mainly driven by the "unknowns" and the unpredictability of plant technical performance after a strong earthquake even in case of successful operation of the seismic shutdown system. The equation used in this case is effectively:

$$HEP_{seis} = HEP_{\min} + HEP_{HRA} - HEP_{\min} \times HEP_{HRA} \tag{1}$$

Here *HEPseis* is the adjusted human error probability in case of a seismic initiator; HEP_{min} is a minimal value for the probability of human error that depends on the acceleration level and the type of action, while HEP_{HRA} is the human error probability as defined in HRA analysis. In technical terms, equation (1) is expressed by the corresponding event tree logic.

Table 2: Human Error Probabilities in Equation (1)

Seismic Initiator	**Type C (Communication with main or emergency control room)**	**Type D (local SAMG action, FLEX type)**
SEIS1 & SEIS2	No impact	No impact
SEIS3& SEIS4	0.0025	Additionally HEP_{HRA}=0.05
SEIS5 &SEIS6	0.005	Additionally HEP_{HRA}=0.1
SEIS7 & SEIS8	0.05	Additionally HEP_{HRA}=0.25

It has to be noted, that in case of failure of main or emergency control room or of the corresponding DC power supplies for instrumentation operator actions that rely on this equipment are guaranteed failed. The dependency of operator actions on hardware are the main contributor to the failure of post-accident operator actions (type C and type D actions).

6. PRA RESULTS AND INSIGHTS

6.1 Main Results

The quantification of the updated Goesgen PRA resulted in an estimate of the total core damage frequency (mean, CDF) of 9.14 x 10^{-6}/a and of the large early release frequency (LERF, mean) of 2.97 x 10^{-6}/a (power operation). The contribution of the different initiator groups to the total CDF is shown in Table **4**. The seismic contribution to CDF makes up 50.8% of the total CDF while the contribution to LERF makes up 65.6% of the total. Besides seismic events, wind and tornado hazards are the main contributor to the core damage frequency caused by external events. Both initiator groups have in common that the hazard assessment results are governed by epistemic uncertainty. Neither significant earthquakes nor tornados have been observed near the NPP Goesgen site since the start of instrumental observation. Internal events, traditionally the focus of PRA development make up only 7.8% of the overall core damage frequency. Approximately 11.5% of core damage accident sequences can be arrested by severe accident management (SAM) action without reactor pressure vessel rupture, causing only small releases of radioactivity within the normal design basis limits. NPP Goesgen introduced SAM guidelines in 2005, implementing additional measures (e.g. an external material storage facility and cooperation with other nuclear power plants and military forces) after the Fukushima accident (similar to the US FLEX approach). About 23% of potential large early releases are mitigated by the filtered venting system of NPP Goesgen. The latter was implemented in 1993 after the Chernobyl accident. In 2018, it was upgraded by the addition of second, iodine retention filter. This additional filter unit enhances the retention of organic iodine, the more radiotoxic species of radioactive iodine.

Table 4: Contribution of Initiator Groups to Core Damage Frequency

Initiator Group	Description	CDF, [1/a]
CINT	Internal events	7.16E-07
CEXT	External hazards	6.67E-06
CINTPH	Internal hazards (including fires and floods)	1.75E-06
Total		9.14E-06

6.2 Insights from Importance Analysis

According to Swiss regulations design and operation of nuclear power plants has to be risk-balanced. None of the initiator groups shall dominate the risk profile of the plant. Safety enhancements are mandatory, as far as achievable by using accepted and sufficiently mature technical and organizational means, as long as either the plant CDF is higher than 10^{-5}/a or the LERF is higher than 10^{-6}/a. The largest risk contribution of a single initiator group has to make up less than 60% of the total risk (CDF or LERF). The results of SPRA are used to identify the potential for further safety enhancement of the plant (PRA application – safety assessment). In RISKMAN™ the risk importance measure RRW (risk reduction worth) for seismic components can be used to estimate the possible safety benefit of further improvements of load capacity of SSCs at NPP Goesgen. RRW for seismic components tells, how much the estimated risk metric (CDF or LERF) can be reduced, by making the corresponding component "perfect". The state of "perfection" can be achieved by increasing the load capacity of the component to "infinity" or by eliminating the consequences of a seismic failure of the component using other technical means, for example, system and design extensions. Table 5 and Table 6 show the RRW values for the most important seismic components for seismic CDF and seismic LERF respectively.

Table 5: Risk Reduction Worth for Seismic CDF

Rank	Seismic Component/ Component Group	Associated Top Events	Component Description	Risk Reduction Worth (RRW)
1	FXX4	SLEAK (seismically induced LOCA inside Containment)	Small Bore Pipework	1.384
2	FXX3	SBYP (seismically induced LOCA outside Containment)	Small Bore Pipework	1.381
3	FPRZ	SLEAK	Pipework connected with Pressurizer	1.154
4	FSGR	SLEAK	Pipework connected with steam generators inside Containment	1.0964
5	CHRLA/CHRLB	SDCLA/SDCLB	DC power supply for reactor protection system and instrumentation	1.064

The results in Table 5 show the high importance of small-bore pipework that might fail under seismic loading. Preventive accident management is not efficient to mitigate the resulting LOCA or bypass-LOCA scenarios. Emergency programs like FLEX are mainly focused on station blackout scenarios, while under seismic conditions the combination of station blackout with small LOCA cannot be ruled out. This is confirmed by the importance values obtained for seismically induced LERF. Small-bore pipework ruptures in the reactor annulus building may lead to a bypass LOCA condition, which is difficult to mitigate just by accident management actions. The available time window for mitigating actions is rather low and the boundary conditions for human performance are heavily degraded by the earthquake consequences. The earthquake and tsunami causing the Fukushima accident large destroyed the external infrastructure. Therefore, the chances for successful external support could be reduced. After an earthquake, civil defense organization may face a large amount of problems even without any accident at a nuclear power station. Based on these insights, the focus of NPP Goesgen safety enhancement program is directed towards fixed on-site installations of accident management systems extending the design of the plant to cope with risk critical scenarios. One of the most important measures planned by NPP Goesgen is the installation of passive Leak-Stop-Valves (LSVs) able to prevent the bypass LOCA scenarios identified. Their installation will contribute both to the reduction of seismic core damage frequency as well as to the reduction of seismic LERF.

Table 6: Risk Reduction Worth for Seismic LERF

Rank	Seismic Component/ Component Group	Associated Top Events	Component Description	Risk Reduction Worth (RRW)
1	FXX3	SBYP (seismically induced LOCA outside Containment)	Small Bore Pipework	6.024
2	CHRLA/CHRLB	SDCLA/SDCLB	DC power supply for reactor protection system and instrumentation	1.064
3	FXX4	SLEAK (LOCA inside Containment)	Small Bore Pipework	1.381
3	FPRZ	SLEAK	Pipework connected with Pressurizer	1.154

6.3 Uncertainty Analysis for SPRA

The results of the uncertainty analysis for the seismic contribution to core damage and to large early release frequency are presented below.

Table 7: Results of Uncertainty Analysis

	5% -Quantile	Median	95%- Quantile	Mean
Seismic CDF, [1/a]	1.446×10^{-8}	1.440×10^{-6}	2.038×10^{-5}	4.646×10^{-6}
Seismic LERF, [1/a]	2.217×10^{-9}	4.306×10^{-7}	8.99×10^{-6}	1.963×10^{-6}

The results show, that the uncertainty is very high. This also illustrated by Figures 4 and 5. The uncertainty covers a range of several orders of magnitude. The empirical range factor of an equivalent lognormal distribution for the seismic core damage frequency is 14.2. For seismic LERF the range factor is even higher and makes up 20.9. The main driver for the large uncertainty is the epistemic uncertainty embedded in the seismic hazard analysis. In general, the uncertainty is slightly reduced in comparison with earlier seismic PRA studies for NPP Goesgen. This is the result of the seismic enhancement program for SSCs and of the installation of an automatic seismic shutdown system.

Figure 4: Uncertainty Distribution – Seismic Core Damage Frequency

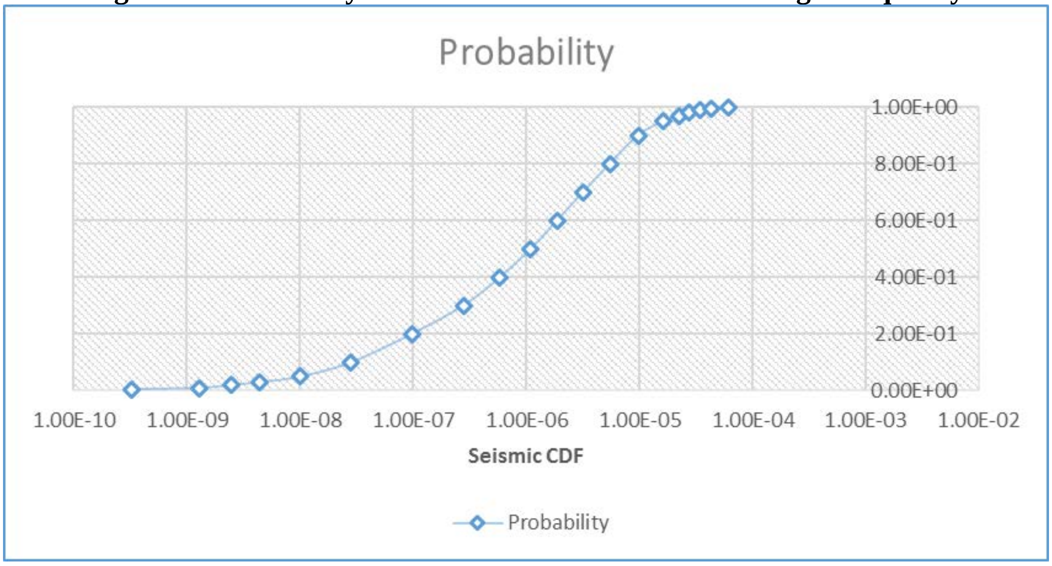
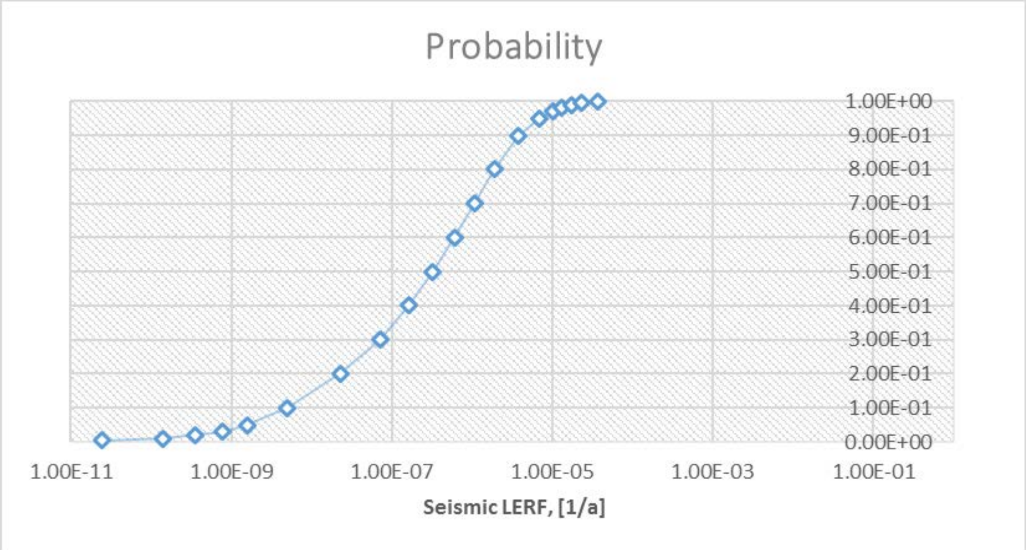


Figure 5: Uncertainty Distribution – Seismic Large Early Release Frequency



6.3 Insights

The results of the updated PRA led to some very valuable insights.

1) Sensitivity studies confirmed the high safety benefit of the new automatic seismic shutdown system. Standard PRA methodology frequently ignores the possibility of pre-initiator transients caused by external hazards like earthquakes. Without an automatic shutdown system earthquakes may cause a plant transient caused by spurious actuation of I&C systems (e.g. of reactor power or turbine power controls followed by intervention of component protection systems before reactor trip) that can affect PRA success criteria (e.g. increased power level) or may induce a LOCA condition by spurious actuation of motor operated valves. Pre-accident transients in a PWR which cause a pressure increase may trigger reactor coolant relief via pressurizer safety valves making a TMI type transient possible. Sensitivity calculations for a worst case bounding scenario with the risk model indicates that without a seismic shutdown system the core damage frequency could by higher by an order of magnitude. The installation of the new seismic shutdown system improves the boundary conditions for operator actions and nearly eliminates the possibility of a seismically induced ATWS.
2) Importance analysis for seismic components confirmed the expected safety benefit of the installation of new passive Leak-Stop-Valves (LSVs) in measurement lines in the reactor annulus building to reduce the risk of containment-bypass accident sequences.
3) Analysis of efficacy of post-accident operator actions including SAMG actions (mobile equipment) did confirm that only actions that rely on equipment not yet used during the accident sequence have a quantifiable chance of success for mitigating accident consequences. This confirms the position of NPP Goesgen that safety enhancements preferably should be performed in form of fixed on site installations rather on the use of mobile equipment.

7. CONCLUSION

An intermediate update of the seismic PRA of NPP Goesgen was completed taking into account the manifold plant upgrades and safety enhancements. The update included an update of seismic fragility analysis. The latter included the use of rather complex models, for example, taking into account the structural coupling between reactor coolant circuit and reactor building structure. The quantification of the risk model (integrated level 1 and level 2 PRA) did show that despite the significantly increased seismic hazard the plant complies with the international safety objectives for new nuclear power plants with respect to core damage frequency (mean CDF below 10^{-5}/a). The planned installation of passive Leak-Stop-Valves in measurement lines helps to reduce the risk from seismically induced containment bypass scenarios. The new automatic seismic shutdown system has a large contribution to the overall risk reduction especially by avoiding pre-accident transients and by improving boundary conditions for operator actions. With further progress of the fragility analysis as well as of further planned safety improvements, the PRA study will be updated again (Living PRA).

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